NASA-DARES website

# NASA Decadal Astrobiology Research and Exploration Strategy (NASA-DARES)

## Draft Report Summary For Community Feedback

https://science.nasa.gov/astrobiology/strategy/dares


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# What is NASA-DARES?

- **Integration Across NASA Science:** NASA-DARES is an Science Mission Directorate (SMD) level effort to unify astrobiology themes across divisions and foundational documents, complementing, rather than superseding, decadal surveys and other consensus reports.

- **Community Input and Gap Identification:** Community input through RFIs, webinars, and formal offline feedback helps identify gaps in existing documents and incorporate emerging scientific developments.

- **Scope of DARES:** DARES broadens the scope of astrobiology across SMD while providing deeper synthesis within key research areas, producing a comprehensive, non-consensus reference for NASA's Astrobiology and Search for Life efforts. NASA-DARES Task Forces 1 & 2 explicitly disclaim any official advisory role to NASA.

- **Use by NASA:** NASA civil servants will review the DARES document as a cross-cutting compendium of decadal findings, consensus report recommendations, science gaps, and emerging developments since these reports were published. This consolidated perspective may help identify opportunities and inform programmatic planning across astrobiology in support of SMD’s search for life objectives.

# How to read NASA-DARES

## NASA-DARES is intended to:

- Synthesize community perspectives, including recent consensus recommendations, into a non-consensus report.
- Identify scientific, technological, and community opportunities, gaps, and emerging needs.
- Highlight connections across NASA Science
- Capture emerging areas of astrobiology research
- Provide context for future planning activities

## NASA-DARES is NOT intended to:

- Rank priorities
- Prescribe funding decisions
- Direct mission selections
- Establish NASA policy
- Replace decadal surveys or consensus reports from the National Academies

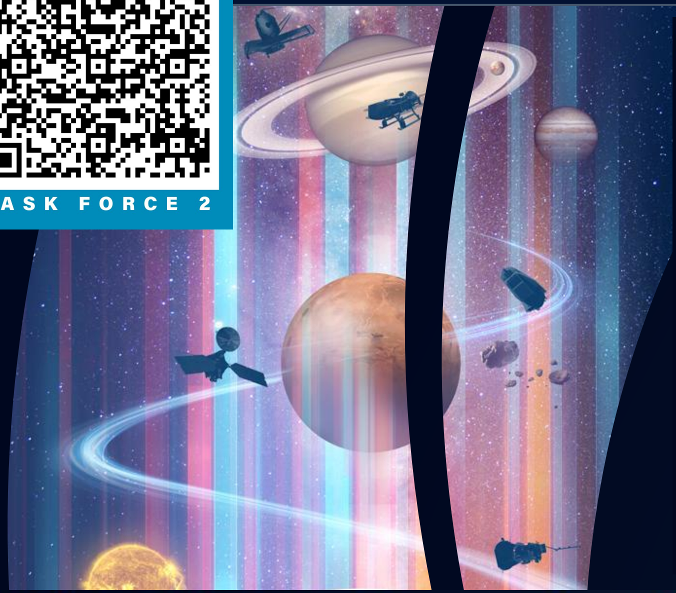
**NASA-DARES is not a decisional document. Inclusion in NASA-DARES signifies relevance to NASA Astrobiology, but should not be interpreted as an indication of future funding, programmatic priority, mission implementation, or agency commitment.**

# How to Provide Feedback

- Please email all public comments to HQ-RFIastrobio@mail.nasa.gov with the subject line “NASA-DARES Public Comment” by 11:59 PM EDT on July 2nd, 2026. Comments received after this deadline will not be considered.
- Please indicate which Focus Area(s) your comment addresses at the beginning of your response.
- Comments may be submitted by an individual or on behalf of a community group, organization, or other collective body.
- Anonymous submissions will not be considered.
- Comments will only be accepted as attached PDF files or as in-line email text.

# NASA DARES Task Forces 1&2: >70 Total Participants

NASA-DARES
TASK FORCE 2



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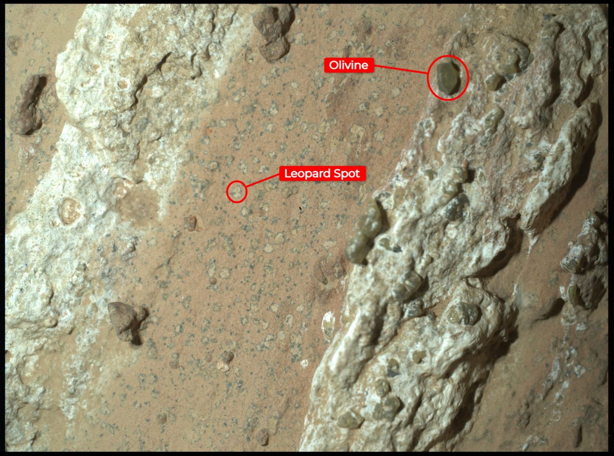
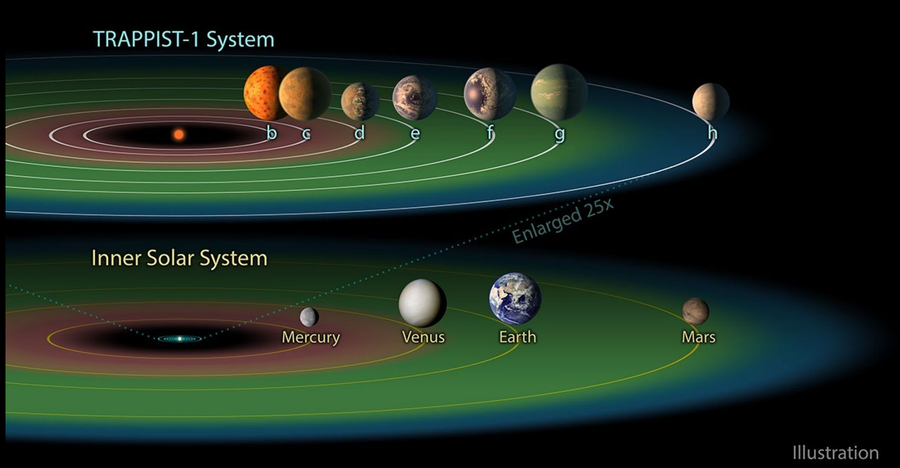
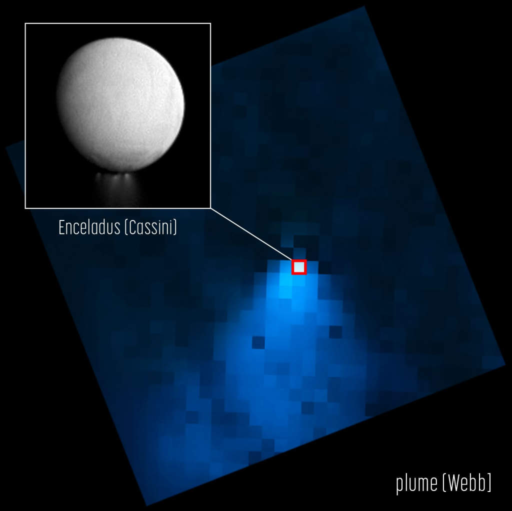
# Building on six decades of progress

- 'Exobiology' first coined in 1960 by Joshua Lederberg
- Modern field of astrobiology created in 1990s
- 2000s: Links to planetary science, 'follow the water'
- 2010s: Exoplanets, sample science
- NASA Astrobiology roadmaps in 1998, 2003, 2008, 2015



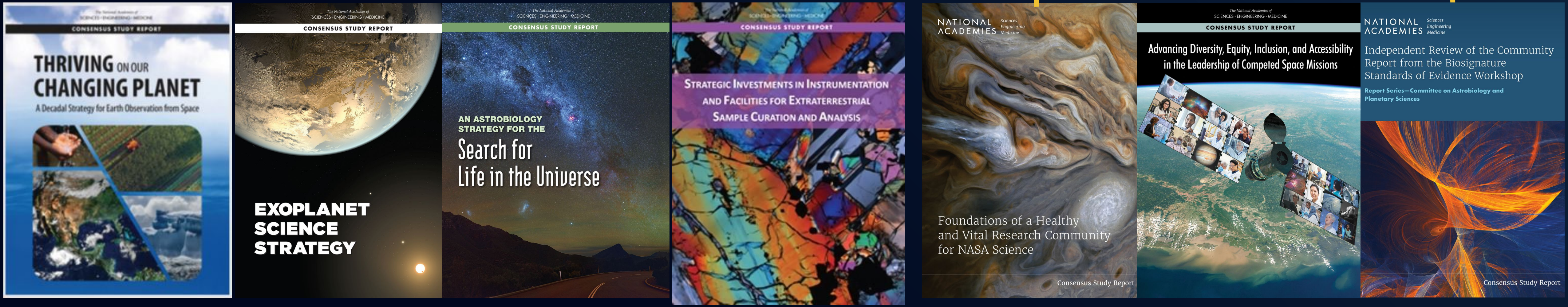



# Progress in astrobiology since the 2015 strategy

- **Rapidly growing connections between NASA science divisions**
- **Exoplanets:** JWST, sub-Neptunes + the radius valley, star-planet interaction, atmospheric loss, rocky planet characterization and theory, ELTs, HWO
- **Mars:** New insights into early habitability and potential biosignatures from Curiosity, Perseverance, orbital data (MAVEN), significant theory and modeling advances
- **Earth evolution and origin of life:** Environmental context for origin of life, new frameworks
- **Venus:** Renewed attention to habitability and evolution, testable predictions for future missions (VERITAS, DAVINCI+)
- **Ocean worlds:** Expansion in our understanding of habitable environments, plume observations, Cassini, Europa Clipper, Dragonfly
- **Planet formation and small bodies:** ALMA, OSIRIS-REx, Rosetta, new ideas on solar system formation
- **Technology and methods:** Big strides in biomolecule extraction and analysis techniques, context-dependent + agnostic biosignatures. More sophisticated planetary protection approaches.

# National Academies Foundational Documents

2018 2019 2021 2022




2023 2024 2025 2026

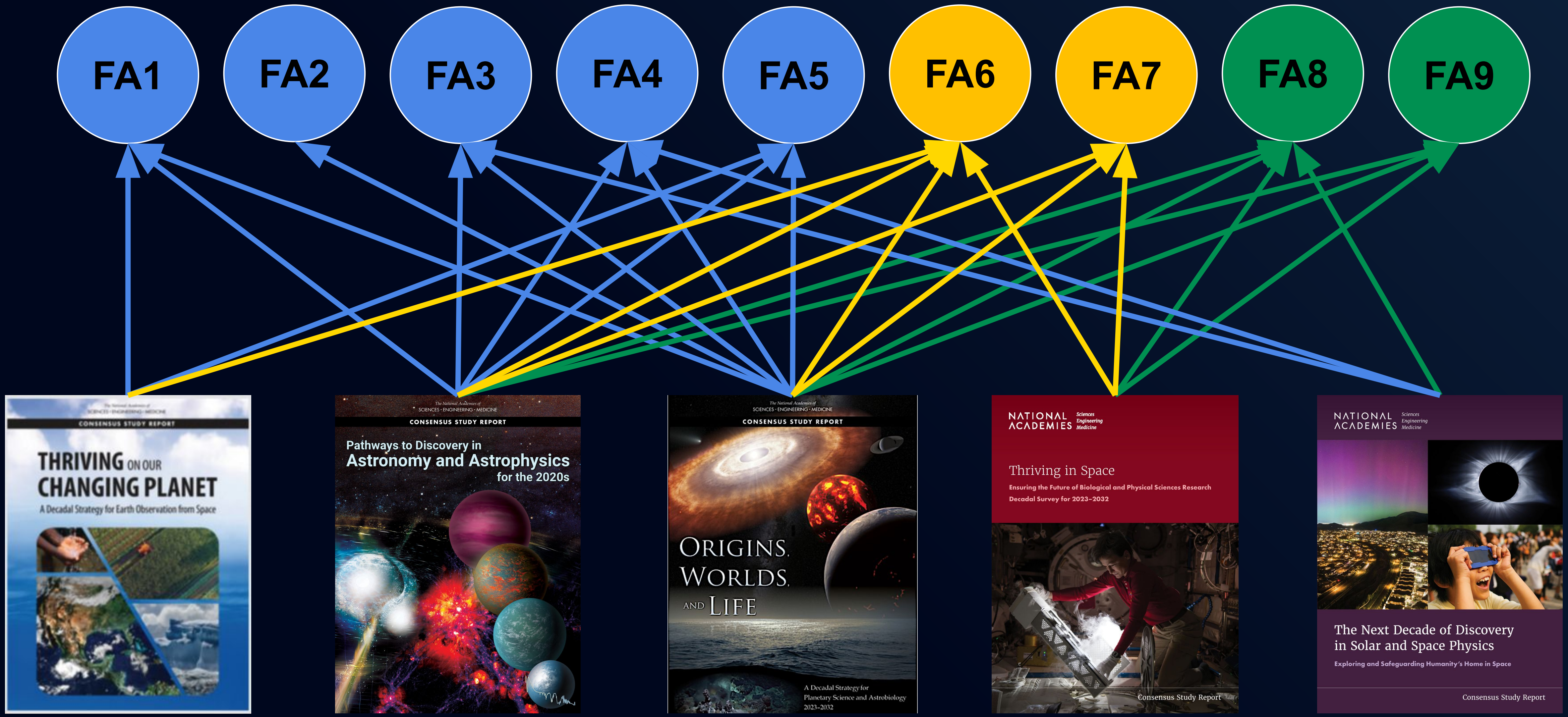
# NASA-DARES Focus Areas

1. Protometabolism and Synthesis/ Function of Macromolecules in Planetary Environments
2. Abiotic Organic Production and Chemical Evolution within Planetary Environments
3. Co-Evolution of Biospheres, Worlds, and Planetary Systems
4. Comparative Planetology to Understand Habitability
5. Detecting Signs of Living Environments and Living Worlds
6. Astrobiology-Focused Mission Approaches and Technology Development
7. Investment in Astrobiology Physical and Digital Architecture
8. Workforce and Early Career Support
9. Astrobiology in Society

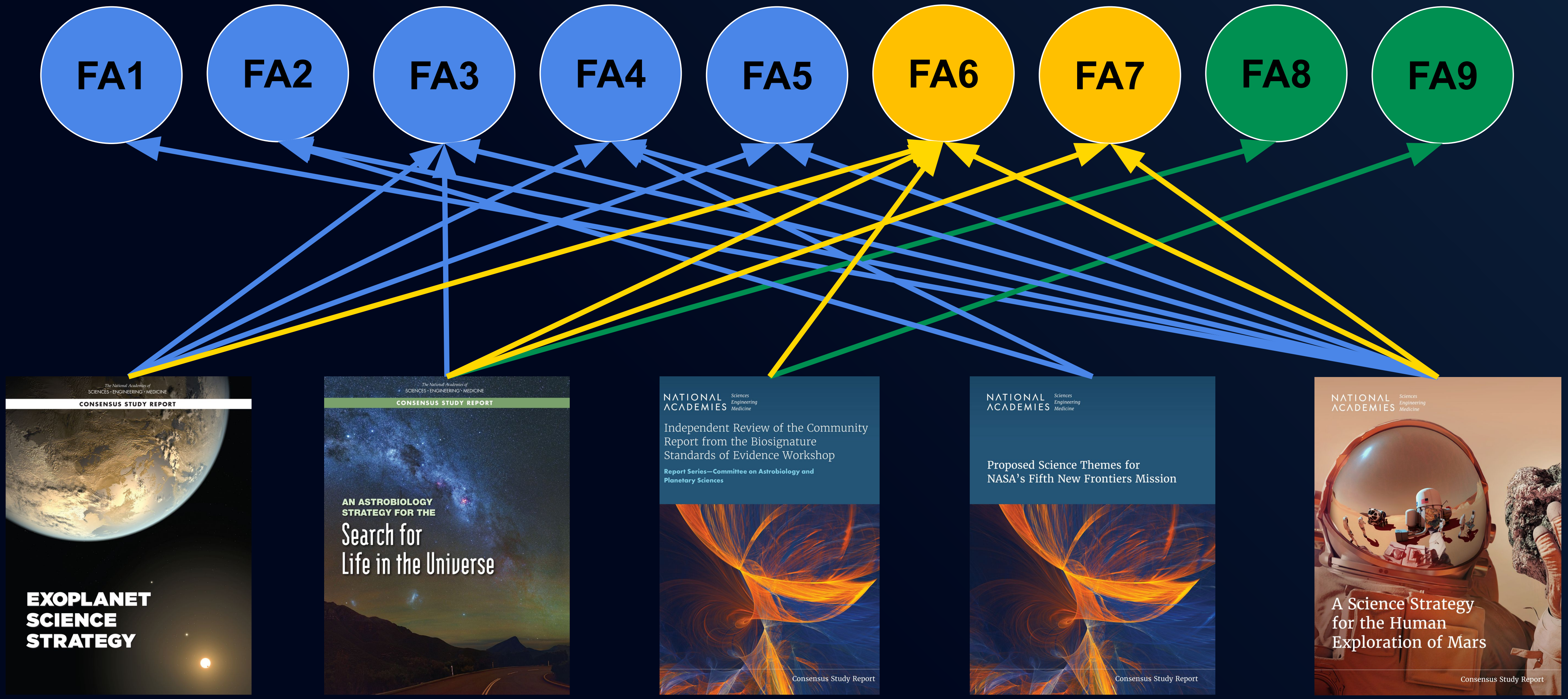
Research | Exploration | Stewardship

**Focus Areas were identified by Task Force 1 via RFI synthesis and finalized via community discussions at the RFI Findings Workshop in Washington, D.C., in May 2025.**

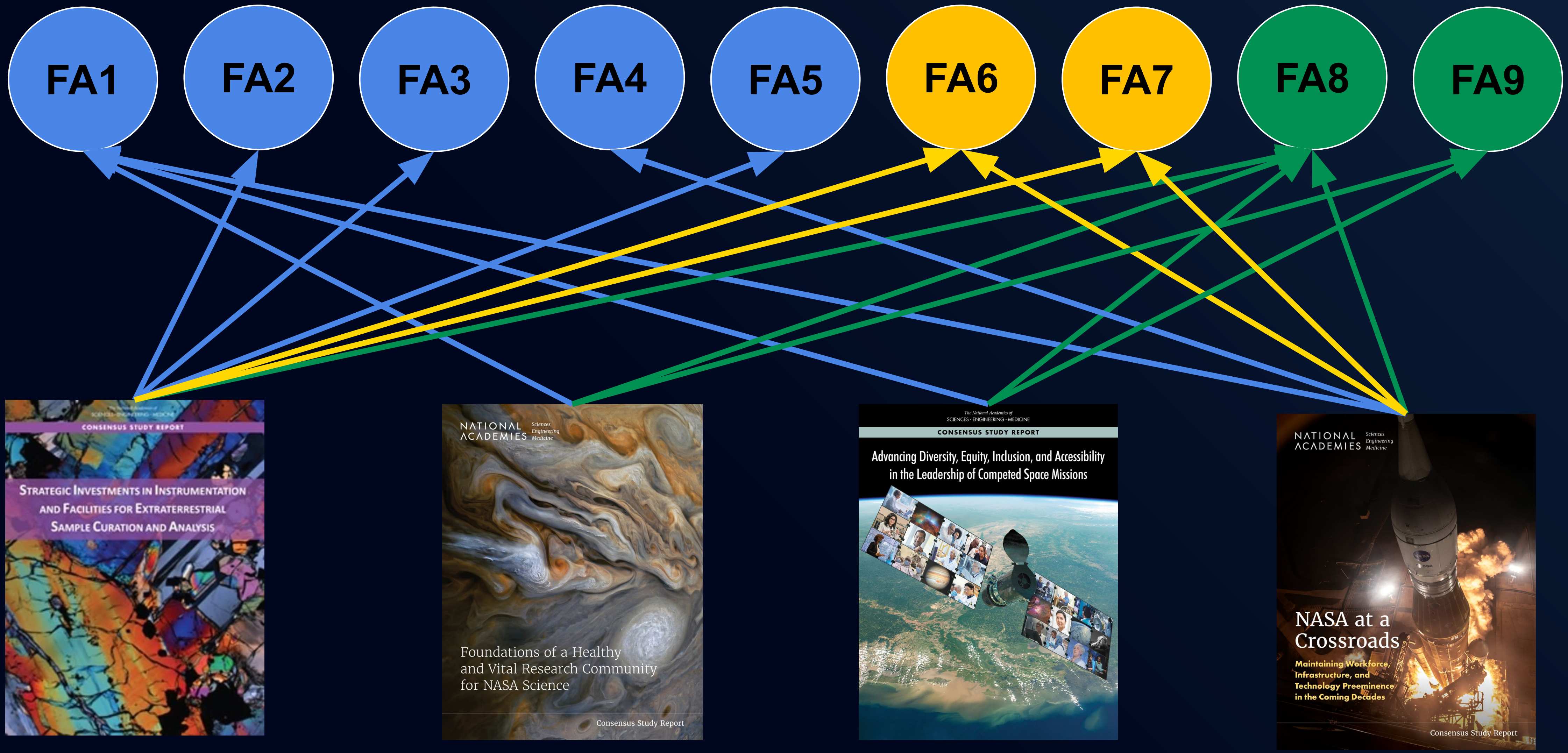
# National Academies Foundational Documents: Decadal Surveys



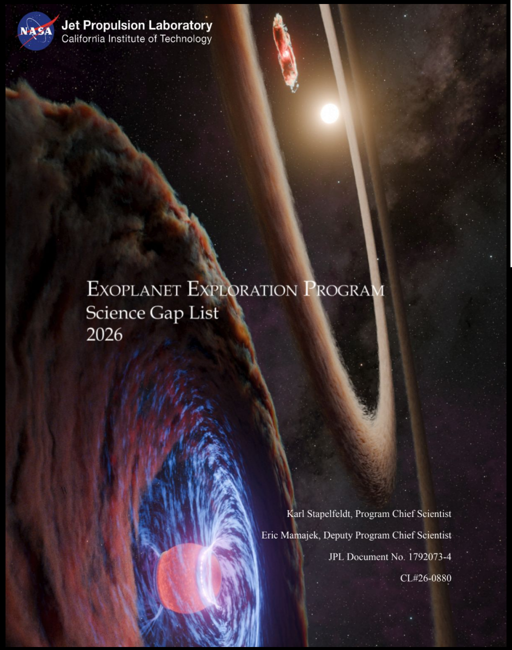
# National Academies Foundational Documents: Targeted Studies



# National Academies Foundational Documents: Exploration and Stewardship



# >50 Additional Foundational Documents




## The Life Detection Knowledge Base:

A NASA Ames-Goddard collaboration to advance life detection mission planning

NASA Silicon Valley Ames Research Center · NASA Goddard Space Flight Center · Center for Life Detection

Svetlana Shkolyar, Alfonso Davila, Craig Everroad, Heather Graham, Tori Hoehler, Niki Parenteau, Marc Neveu, Richard Quinn, Caleb Scharf, Cassie Connolley

## Testing Origin-of-Life Theories with the Habitable Worlds Observatory

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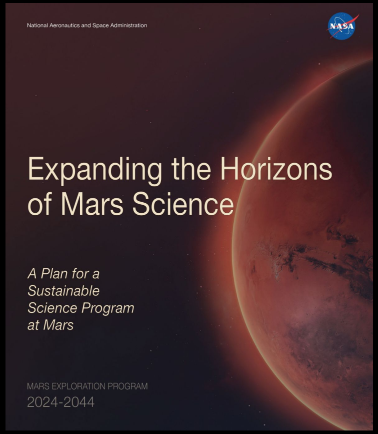
## The Abiotic Background as a Central Component of a Sample Safety Assessment Protocol for Sample Return

Beaty,[1] Heather V. Graham,[2] Gerald McDonnell,[3] Barbara Sherwood Lollar,[4]
[5] Andrew Steele[6]; SSAP Tiger Team, and Rachel Mackelprang[7]

les are being collected and cached by NASA's Perseverance rover, with the as soon as the mid-2030s. Upon return, samples would be housed in a sample al containment to prevent exposing Earth's biosphere to any potential biohaz- ples could be released from high containment for scientific investigations if sterilized. The Sample Safety Assessment Protocol Tiger Team (SSAP-TT) eceiving Project between August 2023 and August 2024 and tasked with the y Assessment Protocol (SSAP). The result of this work is a proposed three- esian statistical hypothesis testing, to assess the risk as to whether returned biology that could represent a biohazard. The proposed protocol outlines pro- e samples could be safely released from high containment without steriliza- ew" step. This article presents the central concept of the SSAP approach— he abiotic baseline. Organic molecules, which exist throughout the solar sys- iotic origins. However, biotically produced organic molecules exhibit distinct ndance characteristics that differentiate them from those formed through abi- rotocol would examine the organic inventory of returned samples by using morphological and spectral assessments, to determine whether any signals is, whether the organic molecular inventory could be explained solely by abi- proach provides a rigorous, yet feasible, safety assessment protocol by using izing sample consumption. We also identify key areas for future research and ection limits and further characterization of the martian abiotic background. —Mars Sample Return—Abiotic baseline. Astrobiology 25, 671–693.




OCSDO
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## 2025 NASA OPEN SOURCE SCIENCE DATA REPOSITORIES WORKSHOP REPORT

Science Mission Directorate

December 5, 2025

# TF1: >130 white papers

# Webinars: 49 topics covered

Research | Exploration | Stewardship

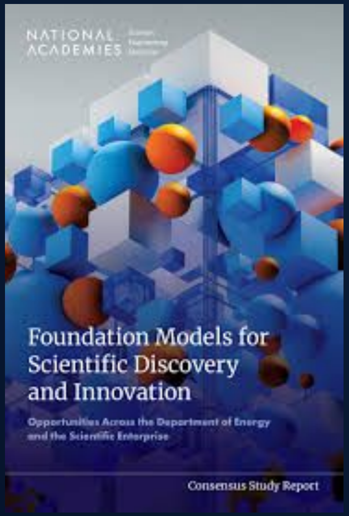
| | February 25, 2026 | March 04, 2026 | March 11, 2026 | March 18, 2026 | March 25, 2026 |
|---|---|---|---|---|---|
| Plenary Panel | Reflecting on the Last Decade of Astrobiology | Emerging Life Detection Opportunities | New Vistas in Astrobiology | Astrobiology, Society, and Human Space Exploration | Mapping Habitability to the Origin of Life |
| FA1 | Chemistry Leading to the Origins of Life and Chemistry of Life | Water, Thermodynamic Cycling, and the Complex Molecules | No breakout session; joined FA8 Office Hours to discuss State of the Profession for OoL Research | From the Origin of Life to the Last Universal Common Ancestor (LUCA) | Earth Conditions Relevant for the Origin of Life |
| FA2 | Abiotic Chemistry in the Planetary Environment | Strategies to Better Characterize the Abiotic Baseline in Ocean Worlds | Abiotic Chemistry in Interstellar Space Relevant for Planets | Volatile Cycling and Abiotic Chemistry in Early Earth Environments | Abiotic Chemistry in Planetary Atmospheres (early Earth, Venus, Titan, exoplanets) |
| FA3 | From Habitability to Evolvability: Conditions for Life's Emergence on Rocky and Ocean Worlds | Co-Evolution of Biosignatures and Worlds (Joint with FA5) | Star-Planet Co-Evolution | Atmospheres, Hydrospheres, and Biosphere-Planet Co-Evolution (Joint with FA5) | Initial Conditions after Planet Formation |
| FA4 | System Level Science: Star System Interactions, Delivery of Water, Asteroids, Etc. | Comparative Habitability of Rocky Worlds (Exoplanets, early Earth, Venus, Mars) | Comparative Planetology and Habitability of Icy to Ocean Worlds | Field Work, Analog Sites, Habitability Modeling, Crossovers with Other Communities (Joint with FA9) | Missions and Exploration as Hypothesis Testing |
| FA5 | Planetary Atmospheres, Exoplanets, and our Solar System | Co-Evolution of Biosignatures and Worlds (Joint with FA3) | Technosignatures | Atmospheres, Hydrospheres, and Biosphere-Planet Co-Evolution (Joint with FA5) | Biosignatures in our Solar System |
| FA6 | Community Need for Shared Sample Repository and Sample Reference Suite | Updates from the Ocean Worlds Working Group (OWWG) and the Search for Life Science Analysis Group (SFL-SAG) | Technology Needs for Astrobiology Exoplanet Missions and Planetary Protection | PESTO Report Update & Quantum Chemistry: From Biosignatures to Instrument Development | Autonomous Labs & Mission Simulation: Implications for Astrobiology Missions and Technology Development |
| FA7 | Open Science and Interoperability for Astrobiology | Digital Data, Repositories, and Metadata | Physical Sample Repositories | AI, Machine Learning, and Other Emerging Tools – A Panel Encompassing Vision, Applications for Astrobiology, Ethics, and Society (Joint with FA6, FA9) | Focus Area Round Table: Identifying and Addressing Community Needs in Astrobiology Infrastructure |
| FA8 | Review Findings/Lessons Learned from DARES Task Force 1 Focus Area 8 | Early Career Support | How Decadal Documents Have Addressed State of the Profession and Progress Toward Recommendations | Community Awareness of Astrobiology Workforce Development Tools, Resources, and Opportunities | Houston, We need a Workforce: Last Call for Your Input |
| FA9 | Integration of Social Science and Humanities in Space Sciences | History and Philosophy in Space Sciences | Strategic Communication in the Context of Basic/Discovery Science | Communicating the Extraordinary: Preparedness, Risk, and Crisis Management in Astrobiology | Cross-Cultural Communication of Astrobiology |

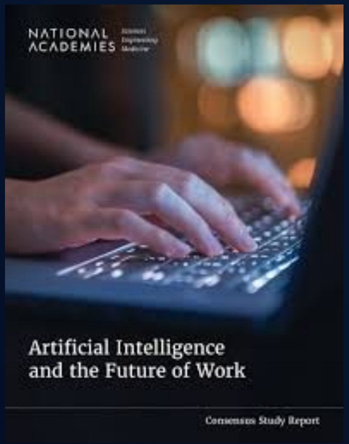
# Cross-Cutting Themes 1/5: Human Space Program

- Humans have high potential to enable new astrobiology science
- The Moon is key for understanding solar system origins and can serve as a testbed for Mars exploration
- Strong yet under-developed synergies between astrobiology and space biology. Applied astrobiology can help advance life support while providing new insights into life in extraterrestrial environments.
- Role of commercial partners in technology and infrastructure is set to increase, bringing new opportunities for low-cost missions
- Key science gaps still exist for planetary protection, and more research is needed to draw down risks for future missions.


# Cross-Cutting Themes 2/5: Artificial Intelligence

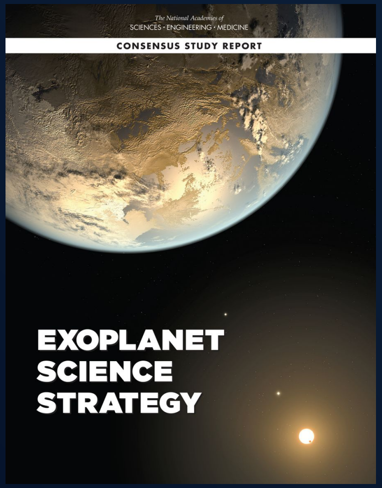
- AI is changing the way we do science and develop technology, and the pace will only increase
- Practical applications include biosignature identification and interpretation, spacecraft/rover autonomous operations, prebiotic chemistry analyses
- Oversight, reproducibility, interpretability and workforce stability are critical issues
- Realizing the positive potential of AI for astrobiology requires programmatic support
- Rapid development since OWL and Astro2020 Decadals underscores need for flexible approach to strategic planning & sustained community input
- Astrobiology offers a framework for understanding AI in context as an emergent property of Earth's biosphere



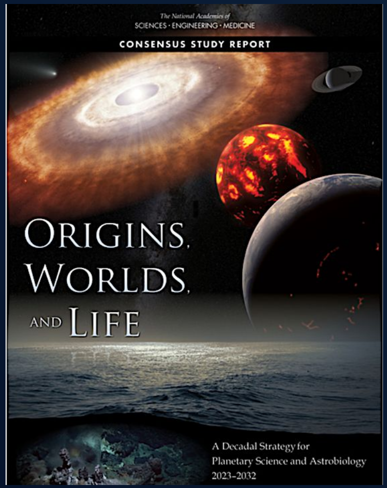
# Cross-Cutting Themes 3/5: Planets as Systems and Origins of Life Research

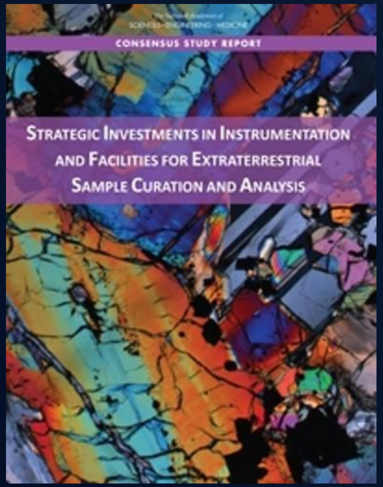
- Planetary bodies should be studied as part of a system (e.g. exoplanet synergies, star-planet interactions) and planetary exploration should not be limited to biosignatures (c.f. Viking)
- System studies need to cover the full range of astrobiology and dynamic nature of habitability: Originability / habitability / life.
- Origin of life (OoL) research needs full integration into astrobiology
- It is essential to characterize the abiotic background in any astrobiology research. Work needed includes research on abiotic chemistry as well as pathways towards planetary complexity.
- Further work is needed in developing understanding of agnostic biosignatures
- Technosignatures research has progressed significantly and can make important contributions in the search for life




# Cross-Cutting Themes 4/5: New Life Detection Technologies and Frameworks

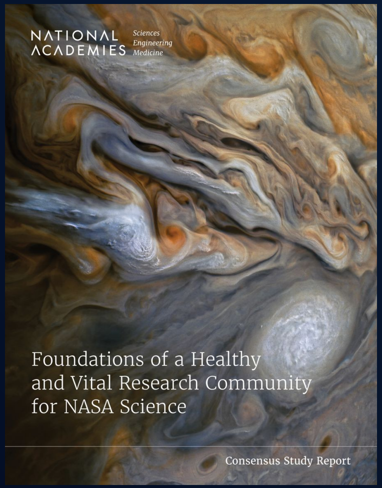
- Effective systems-level approach requires tight integration between overall biosignature / technosignature detection framework, sampling and observing strategy, and instrument technology
- Several promising new technologies (e.g., miniature molecular sensors, high-precision isotopic analysis, nanopore sequencing, coronographs), but more development and investment is needed
- For in-situ sampling (e.g., ice/regolith drilling), collection efficiency and processing yield remain critical unsolved issues
- We need more integrated sampling, curation and data collection strategies and better sample accessibility



# Cross-Cutting Themes 5/5: Access to Resources, Workforce and Communication Issues

- Stewardship of resources and field and lab infrastructure is systematically under-supported
- Repositories and facilities face substantial sustainability challenges placing samples and capabilities at risk
- Institutional support for workforce development is lacking, with impacts at all career stages, but particularly for Early Career Researchers (ECRs)
- We need an agency-wide strategic communication framework that includes risk communication and preparedness assessment, as well as more social scientific data

# NASA DARES Focus Area 1

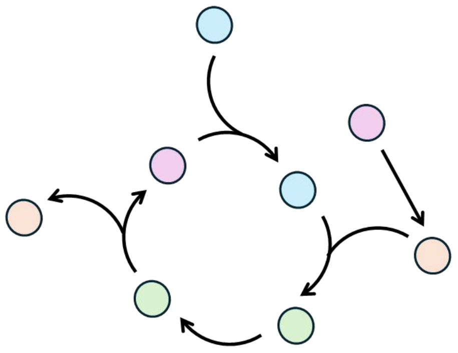
## Protometabolism and Synthesis/Function of Macromolecules in Planetary Environments

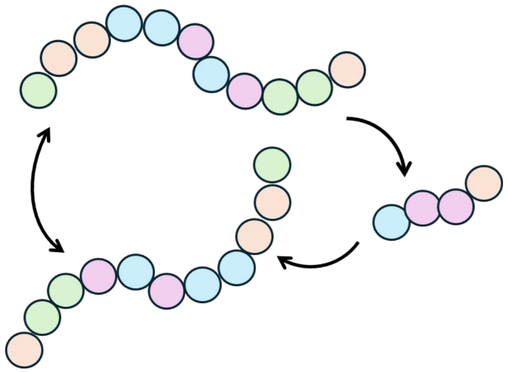
### Focus Area 1 Team

- Laurie Barge, Ph.D. *(Lead)*
- Katherine Dzurilla, Ph.D. *(Executive Secretary)*
- Loren Williams, Ph.D.
- Ulrich Muller, Ph.D.
- Douglas Ruden, Ph.D.
- Fabia Ursula Battistuzi, Ph.D.
- Aaron Burton, Ph.D. *(NASA Ex-Officio Member)*

# Overview

**Astrobiology:** defined as the study of the **origin**, evolution, distribution, future of life





## Origin of Life (OoL) is an inherent and critical part of Astrobiology:

- Studies of the OoL on Earth focus on the nature of chemical evolution, co-evolution of **primitive metabolic systems**, **biopolymers,** cell-like **compartments ('protocells')**, in **planetary environments** that facilitate prebiotic chemistry.
- Studies of the first life (**LUCA** and **pre-LUCA / post OoL**) can tell us about our biosphere and the possibilities for life on other worlds.

**Foundational Document Synergies from the National Academies**

- Origins Worlds and Life Planetary Science Decadal Strategy 2023-2032 (2023)
- Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2023)
- NASA at a Crossroads (2024)
- Foundations of a Healthy and Vital Research Community for NASA Science (2022)
- Advancing Diversity, Equity, Inclusion, and Accessibility in the Leadership of Competed Space Missions (2022)
- A Science Strategy for the Human Exploration of Mars (2026)
- Thriving in Space: Ensuring the Future of Biological and Physical Sciences Research: A Decadal Survey for 2023-2032 (2023)

# FA1 Research Areas

**In the Focus Area 1 chapter of the new astrobiology strategy, we will focus on 3 major research areas:**

1. **From prebiotic chemistry to the origin of life**
   a. **Protometabolism and polymers / macromolecules:** How did protometabolism and early macromolecules arise, evolve, and acquire the capacity for information storage and catalysis in prebiotic environments?

   b. **Compartmentalization into Self Contained Systems:** How did early compartmentalization arise and drive the emergence of membrane-bounded, genetically encoded, energy-generating systems?

2. **Planetary environments that could facilitate prebiotic chemistry or origin of life**

   a. **Geochemical Environment for Prebiotic Chemistry:** How did diverse geochemical environments on early Earth and other worlds enable prebiotic chemistry and the origin of life, including in non-Earth-like conditions?

   b. **Alternative Prebiotic Systems:** How might alternative prebiotic chemistries arise on other worlds, and how can constraining their likelihood inform mission life-detection strategies?

3. **From the origin of life to the Last Universal Common Ancestor (LUCA)**
   a. **The OoL-LUCA Gap:** How did life evolve from its origin to the complexity of LUCA across the missing evolutionary interval?

   b. **Dual Research Approaches:** How do top-down and bottom-up approaches bridge the origin-of-life gap and test whether life's mechanisms are universal across worlds?

# FA1 and AI Influence

- **The inclusion of AI has the potential to limit the historic roles of students/postdocs in research**
    i. "Introductory" wet lab science will become more limited by the inclusion of automated machines.
    ii. Computational science outsourcing of coding work to AI.

- **How could the introduction of AI limit employment of OoL scientists in the future?**

- **Utilizing AI in future grant writing could lead to fraud and drop in proposal quality.** Will there need to be changes to grant review process and grading rubrics to account for AI inclusion?

# FA1 Landscape from NAS and Foundational Documents

- **A study of how AI will impact OoL research is needed.** A NAS study on AI's impact on the Origins of Life and Astrobiology communities is essential for anticipating risks and opportunities in the field.
- **A mid-decadal review should include assessment of FA1 science progress and outlook.**
  a. Assess progress on scientific priorities since previous decadals.
  b. Inclusion of recent (<5 years) missions findings on FA1 science (e.g., Europa Clipper, Perseverance, Curiosity, James Webb Space Telescope)
  c. Assess demographic trends in the workforce
- **Development of best practices for OoL research in public outreach**. (ex: Utilizing science communicators to best communicate to people)
- **The inclusion of cross-disciplinary overlap of OoL study should be discussed in future documents with a wide range of topics.**
  a. ex. Intersection of planetary conditions and the influence of prebiotic chemistry
  b. ex. Incorporation of OoL topics into mission exploration

# FA1 Landscape within NASA (e.g. cross-divisional, cross-directorate)

1. **The OoL community would benefit from more dedicated funding support for origins of life science.**
    a. OoL study should be supported by NASA both through grant funding and inclusion in NASA center infrastructure / core astrobiology capabilities.
2. **Continued investment into OoL training for ECRs.**
    a. Continued support for programs that support ECR in the origins of life community (ex. International Astrobiology Summer School, ECCA, Lewis and Clark, AbGradCon)
3. **Incorporation of OoL research into mission pipeline.**
    a. OoL inclusion in mission concepts and mission development.
    b. Training for OoL researchers and ECRs to increase tangible involvement in NASA missions
    c. Technology demonstrations with OoL research and flight-ready instrumentation and in instrument development

# FA1 Findings (1/2)

**Finding 1:** Research should focus on environments enabling co-evolution of **protometabolism and early polymers**; identifying conditions (e.g., activation, cycling) that reinforce both is key to tracing the transition to self-sustaining life. **(FA1 Research Area 1)**

**Finding 2:** The shift from **chemical** to **Darwinian** evolution marks when polymers begin inheriting sequence information, defining life's origin beyond mere molecular complexity. **(FA1 Research Area 1)**

**Finding 3:** Early life models must include **evolution of compartment permeability**, with initially "leaky" membranes distinct from modern regulated ones; this constrains geochemical conditions enabling early replication. **(FA1 Research Area 1)**

**Finding 4:** Understanding diverse **early Earth microenvironments** (pH, minerals, temperature) identifies prebiotic "laboratories" and defines **range of conditions** enabling or limiting chemical evolution toward life. **(FA1 Research Area 2)**

**Finding 5:** Evaluating **Origin of Life (OoL) potential of worlds** which may be stricter than habitability; worlds may be capable of supporting life yet lack processes for its origin. Identifying OoL bottlenecks informs likelihood of life vs. prebiotic states that may be found on other worlds, including **non-Earth prebiotic pathways**. **(FA1 Research Area 2)**

# FA1 Findings (2/2)

**Finding 6**: Distinguishing the origin of life from Last Universal Common Ancestor is critical, as LUCA was already complex; understanding this missing evolutionary gap informs whether life can transition from chemistry to biology elsewhere. **(FA1 Research Area 3)**

**Finding 7**: Integration of top-down phylogenetic data with bottom-up chemical principles is essential to identify general chemical constraints and transferable biosignatures applicable to non-Earth-like environments, such as icy moons or Mars. **(FA1 Research Area 3)**

## NASA DARES Focus Area 2

# Abiotic Organic Production and Chemical Evolution within Planetary Environments

### Focus Area 2 Team

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- Timothy Lyons, Ph.D.
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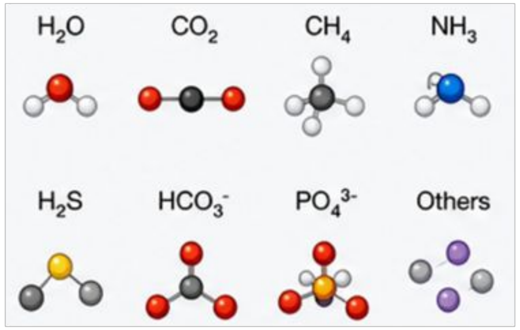
# Overview

Focus Area 2 highlights the importance of **exploring abiotic organic chemical pathways** across a wide range of planetary environments, including those that are not traditionally considered habitable. Investigating these settings provides critical insights into chemical bottlenecks, abiotic baselines, and the environmental controls on molecular evolution.

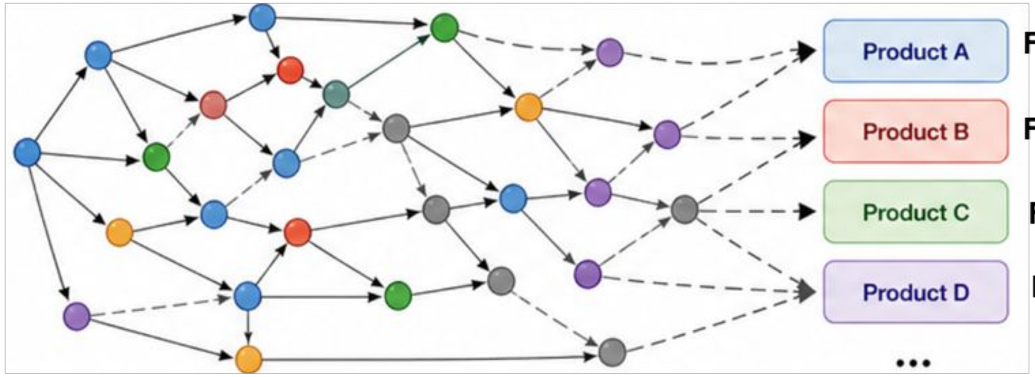
## 1. Chemical Complexity: Multiple Pathways, Multiple Drivers

**Simple precursors**




**Multiple pathways**

**Diverse products**




**Favored under high pH**

**Favored under low temperature**

**Favored under high redox state**

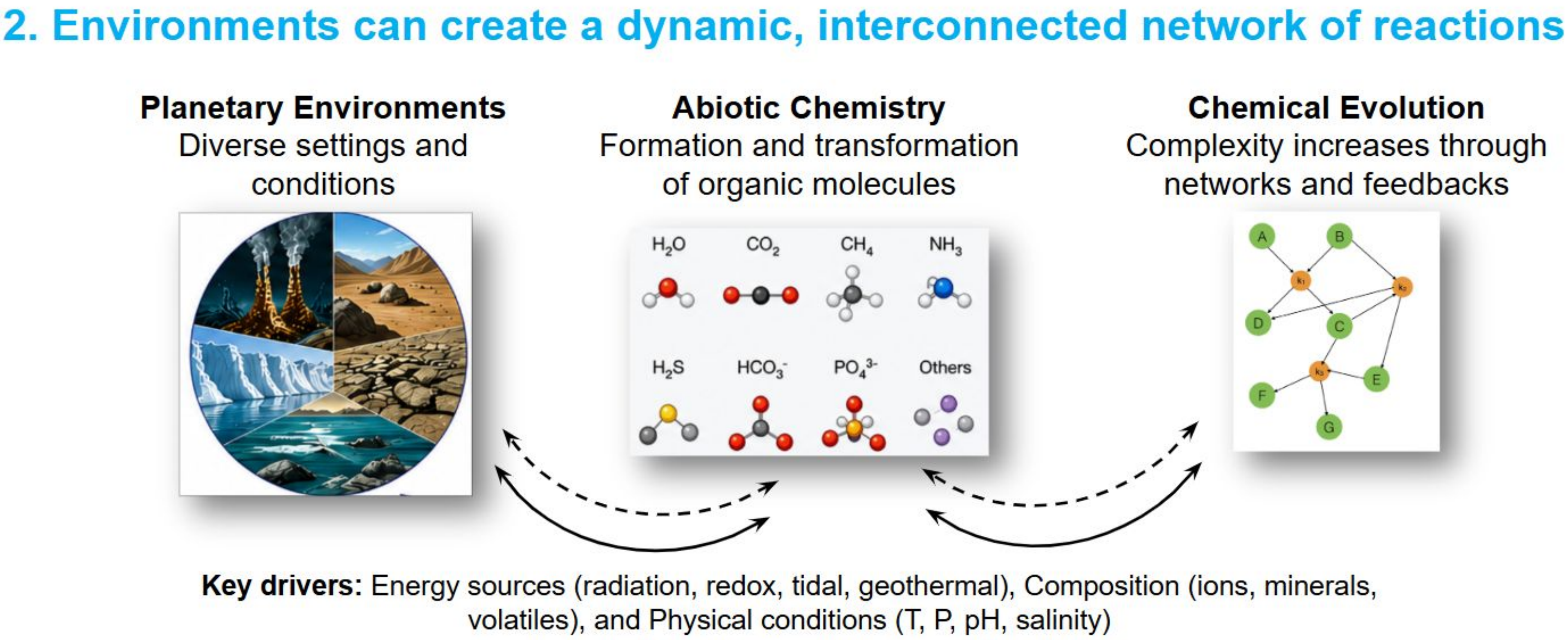
**Favored under high pH**

Pathways branch and intersect: small changes in conditions lead to different products and complexity

**Understanding abiotic organic synthesis is key to understanding the origin of life**

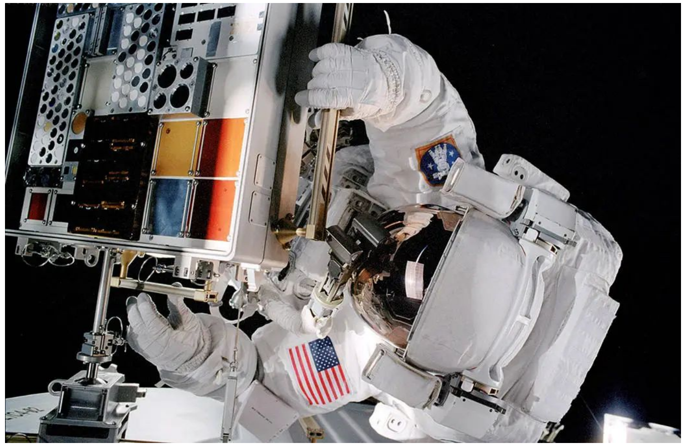
# Overview

Focus Area 2 highlights the importance of exploring abiotic organic chemistry **across a wide range of planetary environments, including those that are not traditionally considered habitable**. Investigating these settings provides critical insights into chemical bottlenecks, abiotic inventories, and the environmental controls on molecular evolution.



# Key activities relevant to abiotic chemical evolution include:

- ❑ Laboratory studies - including potentially long-term studies (>3 yrs)
- ❑ Studies of ancient Earth materials
- ❑ Astromaterials
- ❑ Planetary missions, including human exploration
- ❑ Telescopic observations of planetary surfaces
- ❑ Computational simulations and models to probe gas- and solid-phase interactions
- ❑ New since 2015 Strategy: Use machine learning techniques on large chemical datasets



Astronauts can enable unique condition testing for abiotic chemistry. Credit: NASA

# Why this Focus Area Now?

## 2015 NASA Astrobiology Strategy:

1. **THEN:** Identifying abiotic sources of organic compounds focused on helping understand the origin of Biological Building Blocks to establish the inventory of organics for the OoL on Earth
2. **THEN:** Abiotic chemistry in Earth-like conditions (early Earth or elsewhere) or small bodies that could could deliver or promote formation of Earth-like life
3. **THEN:** Mentioned alternative biochemistries, but not emphasized
4. **THEN:** Elucidate conditions for habitability

Topic 1. Section 1.4 I-IV;
Topic 6. Section 6.5 II & IV

## 2026 NASA-DARES Strategy

1. **NOW:** this topic is not constrained to abiotic sources for the biological building blocks for Earth-like life, but includes studies of the full inventory of abiotic chemical reactions
2. **NOW:** Expands the study to include abiotic chemistry on worlds habitable for Earth-like life, on exoplanets and other environments with diverse conditions
3. **NOW:** Investigate chemical evolution & functionality of non-biological molecules
4. **NOW:** Interpolate to conditions for OoL including distinction of abiotic/prebiotic and emphasising polymerization
5. **NOW:** Leverage existing missions and human space exploration and technology demos to investigate abiotic inventories

# Relevance highlighted in other foundational documents

## NASEM OWL Decadal Survey

- Q3 Origin of Earth and Inner Solar System Bodies
- Q6 Solid Body Atmospheres, Exospheres, Magnetospheres, And Climate Evolution
- Q9.1 What were the Conditions and Processes Conducive to the Origin and Early Evolution…
- Q9.5 How do Record Bias, Preservational Bias False Negatives, and False Positives Play a Role…
- Q10.4 Organic Synthesis and Cycling: Where and How are Organic Building Blocks…
- Q11.1 Path to Biogenesis: What is the Extent and History of Organic Chemical Evolution…
- Q12 Exoplanets

**OWL thoroughly discusses detecting 'false-positives', potential sources & likelihood of such detections in different planetary environments. FA2 identifies a key opportunity for increased attention to chemical evolution and abiotic organic matter beyond Earth-centric prebiotic chemistry.**

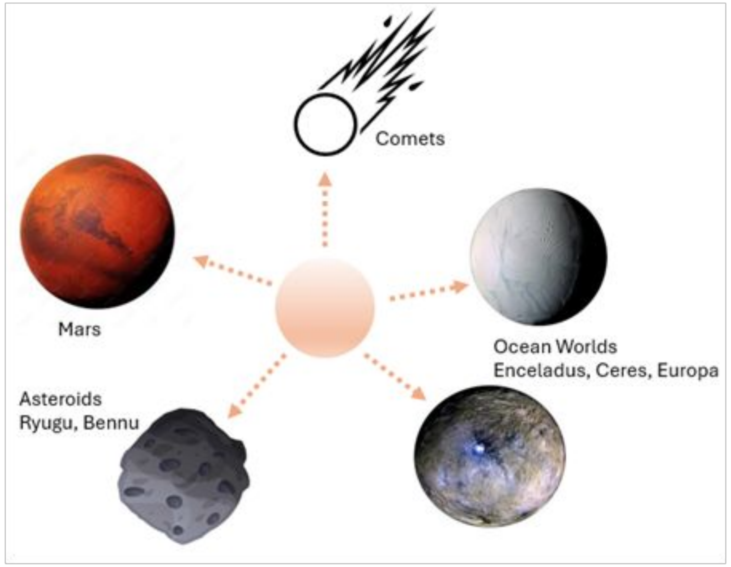
## NASEM Astrobiology for Human Exploration of Mars

- Science Objective 1: Determine if, in the exploration zone, evidence can be found for any of the following: habitability, indigenous extant or extinct life, and/or indigenous prebiotic chemistry
- Appendix B "Panel on Astrobiology: Context for Science Traceability Matrix" (complexity of organic chemistry is identified)

# Findings

## Abiotically synthesized organics are widespread across the Solar System

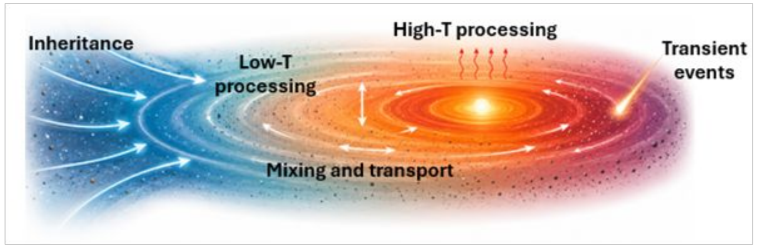
Organics are detected in diverse, non-Earth-like environments.




Organic chemistry is ubiquitous, not unique to Earth.

## Protoplanetary Disk Processing vs Inheritance: Setting initial conditions for habitability

Protoplanetary disk is a highly dynamic environment.




*Inheritance:* Interstellar material inherited into the disk
*Low-T processing:* Formation of ices and organics, aqueous alteration
*Mixing and transport:* Radial and vertical redistribution of materials
*High-T processing:* Crystallization, dehydration and thermal processing
*Transient:* Thermal events and shock processing

Protoplanetary disk processes are an important control on the initial chemical and isotopic compositions of organics.

## The role of impacts in delivering volatiles and light elements is important but remains uncertain

Two end-member scenarios compete.

Single major early event

Prolonged accretion

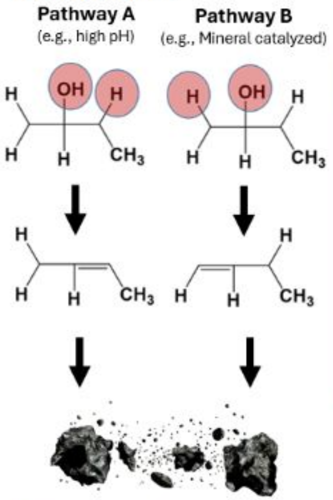
Different delivery histories lead to different initial organic inventories.

# Findings

## Observed abundances, precursors and conditions affect and are affected by underlying reactions mechanisms

Same products can form via different pathways and conditions.

Molecular ratios act as ”frozen-in” probes.




**Measured small molecule ratios**

$CO_2$ / $NH_4$

$NH_3$ / $N_2$

$H_2$ / $H_2O$

$H_2S$ / $SO_2$

....

**Infer interior conditions**

pH

Energy

Temperature

Redox State

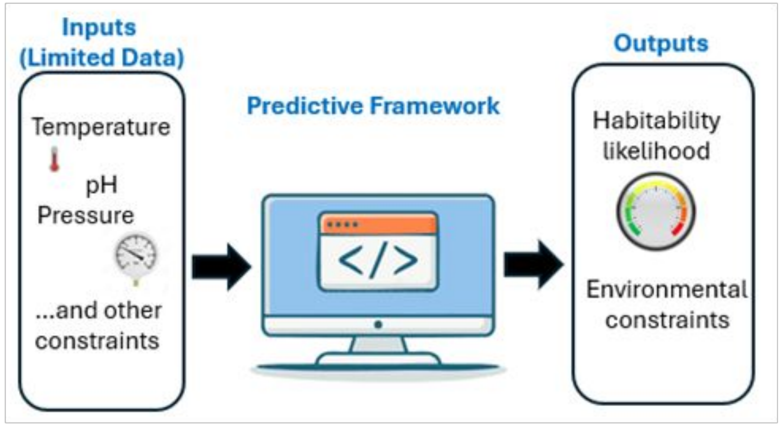
Salinity

Water-rock interaction

Understanding mechanisms and compositional ratios is essential for interpreting habitability and the abiotic baseline in any measurement.

## Predictive frameworks pinned to systematic laboratory experimentation and verification are needed to assess habitability

Modes integrate sparse observations with key processes to constrain scenarios.

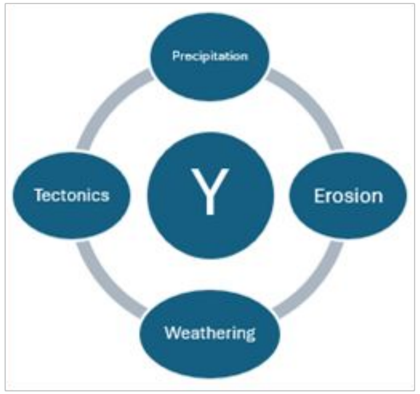



Enables decision-making under uncertainty essential to new targets.

## Tectonics, precipitation and weathering control long-term habitability and element cycling on a planetary body

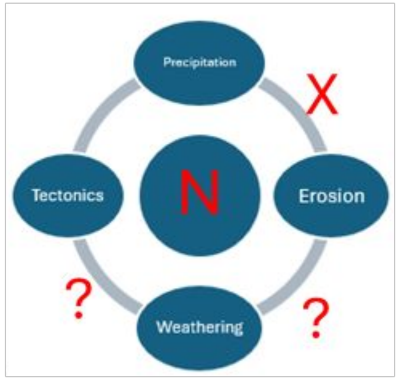
Sustained atmospheric regulation require geochemical cycling.

Earth (active cycling)




$CO_2$ regulation

Other planetary worlds




Weak $CO_2$ regulation

Without active cycling, key elements are consumed and gas regulation is limited.

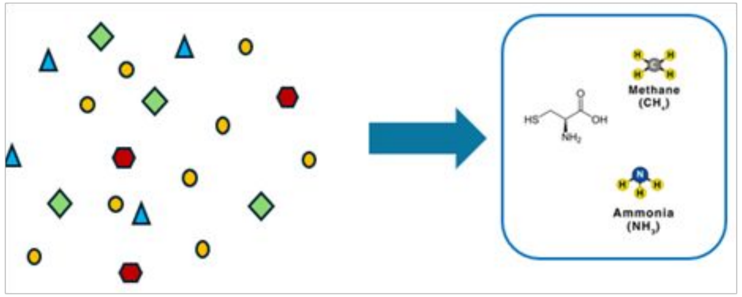
# Findings

## The inventory we observe is diverse; life selects a narrow subset

Abiotic inventories are context-dependent while life concentrates specific molecules.

Abiotic inventory (diverse and broad)

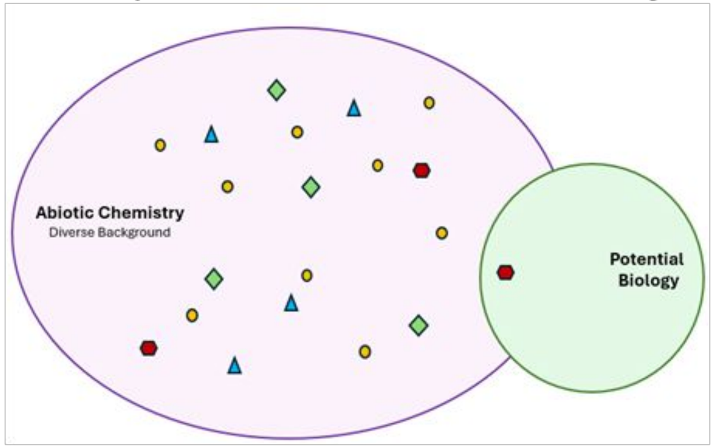
Life selects a narrow subset




Life appears to select and concentrate only a narrow subset from the available pool.

## Agnostic detection techniques and models are needed to distinguish biology from any abiotic baseline

Biological signals are subtle and overlap with the abiotic chemistry.




*Overlap region requires context, multiple lines of evidence, and robust analytical techniques.*

Avoid pre-assuming Earth-like biomarkers; instead, use context and patterns to establish biosignature likelihood.

## *Two sides to the same coin*

Analysis of planetary samples in life detection missions is informed by abiotic chemistry and understanding the baseline of abiotic signals in these analysis is key to successful life detection strategies.

If life is not found in extraterrestrial samples, **it is not a negative result**. The understanding of abiotic chemical systems will enable key insights into understanding how life formed on Earth and can evolve elsewhere.

# NASA DARES Focus Area 3

## Co-Evolution of Biospheres, Worlds and Planetary Systems

### Focus Area 3 Team

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- Prajkta Mane, Ph.D.
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- Jessica Lee, Ph.D. *(NASA Ex-Officio Member)*

# Overview

## The Key questions:

- How does the evolution of the planetary environment affect habitability and the evolution of organic molecules and life?
- In return, how does life affect the planetary atmosphere, hydrosphere, lithosphere in observable ways?

## The Conceptual Landscape:

- We identify the need for a more targeted focus on gaps in our knowledge, and opportunities to close them in the next 10-15 years.

## NASA's Posture:

- Current and upcoming missions are enabling progress in understanding planetary environment evolution, NASA funds relevant community work on biological systems. Furthermore, programs supporting human exploration of the solar system recognize solar system evolution, the study of habitability, and the search for life as top science priorities.

# Theme 1: Initial Conditions

*This theme covers the processes leading up to planet formation and shortly after planet formation (magma ocean composition, etc.)*

Availability of key chemicals:

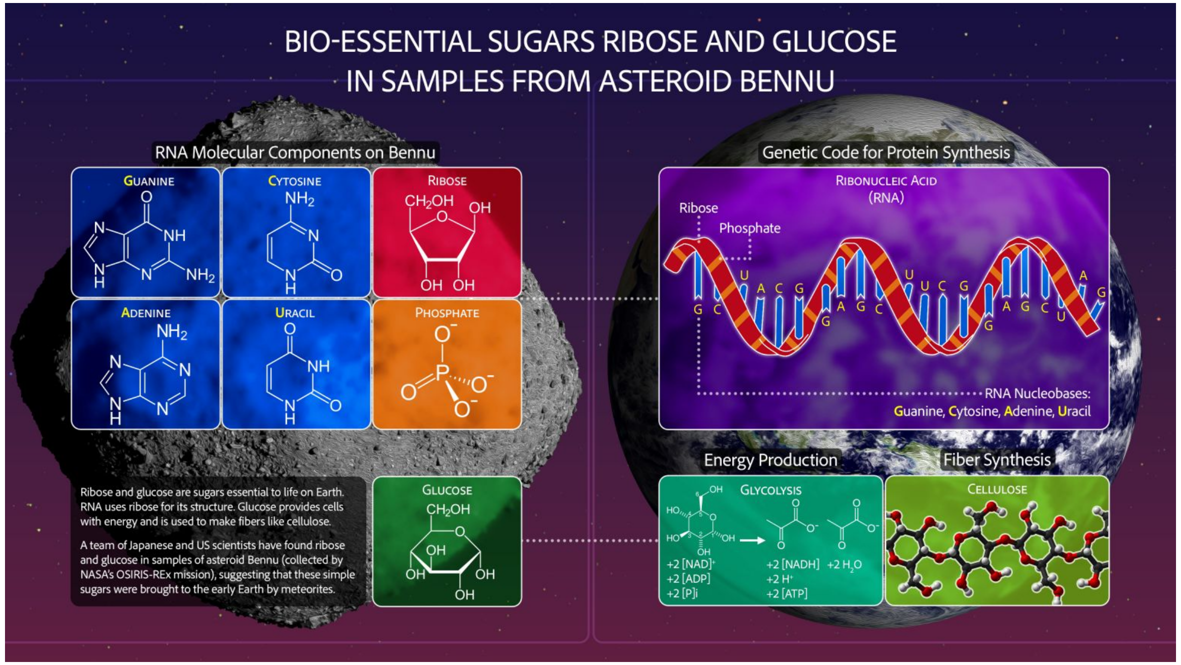
1. What is the origin and evolution of organic matter in the Solar System?
2. What role did asteroids and comets play in the delivery of volatiles and organics to the terrestrial planets?

Initial conditions pertaining to planet formation, stellar materials:

1. What processes created and destroyed organic materials in the Solar Nebula?
2. How does thermal and aqueous alteration alter organic matter in asteroids, comets and terrestrial planets?

Variation in conditions vs. planet size, atmosphere mass, etc.

New hypotheses for transient reducing atmospheres (Zahnle et al PSJ 2020, Wordsworth et al. 2021 Nat. Geosci.), potential more favorable for life's origin.




*NASA's OSIRIS-REx mission detected the bio-essential sugars ribose and glucose, along with nucleobases, phosphate, and amino acids in samples of asteroid Bennu, suggesting that the molecular ingredients of life could have been delivered to early Earth by meteorites.*
*Image Credit: https://svs.gsfc.nasa.gov/14932 Dan Gallagher*

**Finding:**
We need samples for laboratory analyses from diverse Solar System targets, including comets (whose cold environments preserve interstellar and circumstellar material by preventing secondary alteration), water worlds such as Ceres (to test how far prebiotic chemistry can progress in long-lived aqueous environments without sunlight), Mars, and outer Solar System moons including Enceladus, Europa, and Titan. These laboratory studies must also be linked with remote observations from exoplanet surveys.

# Theme 2: Originability

*This theme covers the period after magma ocean solidification and up to the origin of life. We identify a need to distinguish between* ***originability****, habitability, and life going forward, each is a distinct concept.*

**Originability:** the conditions required to drive abiogenesis, including the environments capable of maintaining those conditions (Deamer et al. Astrobiology 2022).

1) Identify materials used by all life on Earth (e.g., lipids, nucleic acids, carbohydrates, proteins, energy carriers, central metabolites, metal ions, redox disequilibria)
2) Study reactions/processes for assembling those materials (e.g., dehydration, polymerization, condensation, phosphorylation, concentration)
3) Search for environments capable of driving those reactions and providing energy & power (e.g., hydrothermal vents, hot springs (Djokic et al Nature Communications 2017), tidal pools)
4) Determine if origin in those environments requires planet-wide conditions and cycles, or if it can proceed locally - e.g., what rate (if any) of surface-interior exchange is needed? (Moore & Webb Nature 2013). What planetary processes are needed for hydrothermal vents and other redox coupled locations? Are they observable? Are they common beyond Earth?)

**Finding:**

**Originability** remains unconstrained with a sample size of 1, including the range of physical and chemical conditions needed. Continued characterization of organic matter and prebiotic chemistry in ancient Earth rocks is needed. Future missions should work to identify the extent of prebiotic chemistry on icy bodies (Titan, Enceladus) and study the **accessible**, likely **uninhabited** bodies (the Moon, Ceres) to determine how complicated prebiotic chemistry can get on these types of worlds.

TABLE 14-1 Organic Inventory of Worlds Throughout the Solar System to Date

| Body | Organics[a] Detected or Predicted to Date | Complexity | Reference(s) |
|---|---|---|---|
| Mercury | Possibly cold-trapped volatiles (C, H, O, and N-bearing species), aldehydes, amines, alcohols, cyanates, ketones and organic acids, refractory (tholin-like) organic materials | Low | Zhang and Paige, 2009; Delitsky et al. 2017; Hamill et al. 2020 |
| Venus | Possibly HCN, methane, ethane, ethene, and benzene | Low | Johnson and de Oliveira 2019, Mogul et al. 2021 |
| The Moon | Possibly methane and other cold-trapped volatiles (C, H, O, and N-bearing species) | Low | Zhang and Paige, 2009; Colaprete et al. 2010 |
| Mars | Methane, chlorobenzene, dichloroalkanes; thiophenic, aromatic, and aliphatic compounds | Low/ Moderate | Freissinet et al. 2015; Eigenbrode et al. 2018 |
| Ceres | Aliphatic organic, possibly amines | Low | De Sanctis et al. 2018; Raponi et al. 2021 |
| Europa | C≡N, C-H functional groups, refractory (tholin-like) organic materials | Low | McCord et al. 1998; Chyba and Phillips 2002 |
| Ganymede and Callisto | C≡N, C-H functional groups, possibly refractory (tholin-like) organic materials | Low | McCord et al. 1997, 1998 |
| Enceladus | Methane, other hydrocarbons, aromatics, amino acids, small and large (macromolecular) O-, N-bearing organics with ethoxy, hydroxyl, and carbonyl functional groups | Moderate | Postberg et al. 2018; Waite et al. 2006; Steel et al. 2017 |
| Titan | Hydrocarbons, nitriles, aromatics, heterocyclic species, acetylene, ethylene, cyanoacetylene, other N- and O-bearing species, nucleobases, amino acids, heteropolymeric species up to 10,000 Da, refractory (tholin-like) organic materials | High | Brown et al. 2010; Lunine et al. 2020 |
| Uranian satellites | Possibly refractory (tholin-like) organic materials (could also be amorphous pyroxene) | Low | Cartwright et al. 2018 |
| Triton | Ethane, hydrocarbons, acetylene, nitriles, heteropolymers, refractory (tholin-like) organic materials | Low | Thompson et al. 1989; Quirico et al. 1999 |
| Pluto | Methane, acetylene, ethylene, HCN, cyanoacetylene, amino acids, nucleobases, refractory (tholin-like) organic materials | Low/ Moderate | Cruikshank et al. 2019 |
| Comets | Acetylene, methane, methanol, formate, methylamine, ethylamine, PAHs, aromatic nitriles, amino acids, refractory (tholin-like) organic materials | Low/ Moderate | Wickramasinghe and Allen, 1986; Clemett et al. 2010; Altwegg et al. 2016 |
| Asteroids | Hydrocarbons, polyaromatic carbon, refractory (tholin-like) organic materials | Low | Cruikshank et al. 1987; Chan et al. 2021; Fink et al. 1992 |

[a] An organic molecule is one that contains at least one carbon atom bonded to hydrogen.
NOTE: Black text represents organics detected via remote sensing or in situ measurements; blue text represents compounds predicted by laboratory experiments/modeling. Complexity is compared to Earth as baseline (see Chapter 12).

*2023 NASEM Planetary Science and Astrobiology Decadal Survey*

# Theme 3: Habitability

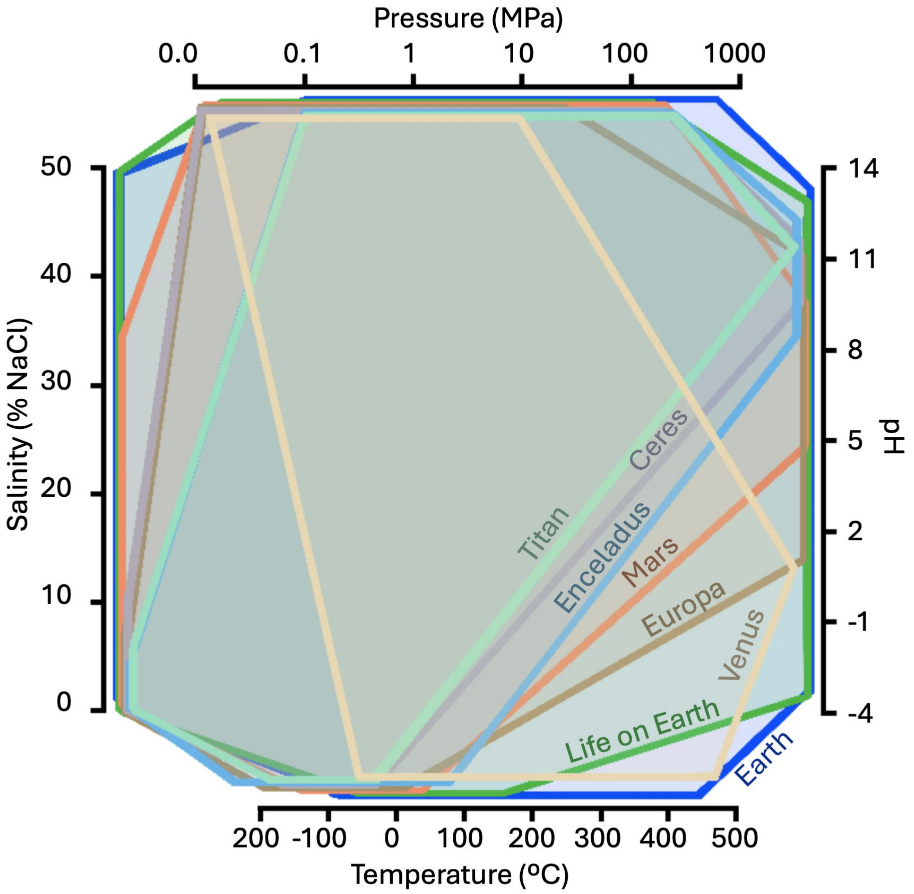
*This theme covers the period after the origin of life and up to today.*
*We identify a need to distinguish between originability, **habitability**, and life going forward, each is a distinct concept*

**Habitability:** The conditions required to maintain life, including the environments capable of maintaining those conditions (pockets of habitability on an otherwise uninhabitable planet)

Work is needed to constrain the habitable environments on:
- Subsurface oceans with little to no atmosphere exchange or insolation (icy worlds)
- Ocean worlds in the habitable zone with atmospheres (super-Earths?)
- Worlds with both land and ocean exposed to an atmosphere

Life as we know it requires redox disequilibrium. In environments with limited access to the sunlight and oxygenic photosynthesis (icy worlds, ocean lithosphere), how do planets maintain redox equilibrium (e.g., through plate tectonics)? What is the range of planetary environments which can sustain redox disequilibrium?

**More work is needed to identify the observable features associated with planetary habitability, including the features of an uninhabited but habitable planet.**




*pH and salinity bounds are projections. Adapted from [Merino et al. 2019](#) Living at the Extremes: Extremophiles and the Limits of Life in a Planetary Context*

<u>**Finding:**</u>
Habitability constraints continue to be refined by the observed limits of extremophile life on Earth. Given these environmental constraints, we now need to identify the full range of observable features associated with habitability, and their false positives.

# Theme 4: Living Planets

*This theme covers the period after the origin of life and up to today.*
*We distinguish between originability, habitability, and* ***life***

Life changes its environment. We need to continue to characterize

Originability and habitability have distinct signatures that we should identify to reduce the chance of **false positive** and **false negative detections of life**.

-There can be prebiotic chemistry without originability and life
-There can be habitable planets which are not inhabited
-There can be living planets which are not (or were never) originable
-There can be an originable planet which is not habitable

**Abiotic baseline**: What does a habitable planet without life look like? How can a habitable planet without life trick us? (false positive biosignature)

We also need to consider the many planets that have no solar system analogs:
-How can sub-Neptunes produce atmospheric gas ratios we associate with life on Earth?
-Redox evolution and redox layering can give false positives for gases (and combinations of gases) as biosignatures. (e.g., Meadows et al. Astrobiol. 2018)
-Planetary-wide complexity and organization as a biosignature (maximum entropy production)
-How can planetary conditions limit life's growth (e.g., having limited copper)?

-How does dispersal across time and space support the development of communities?

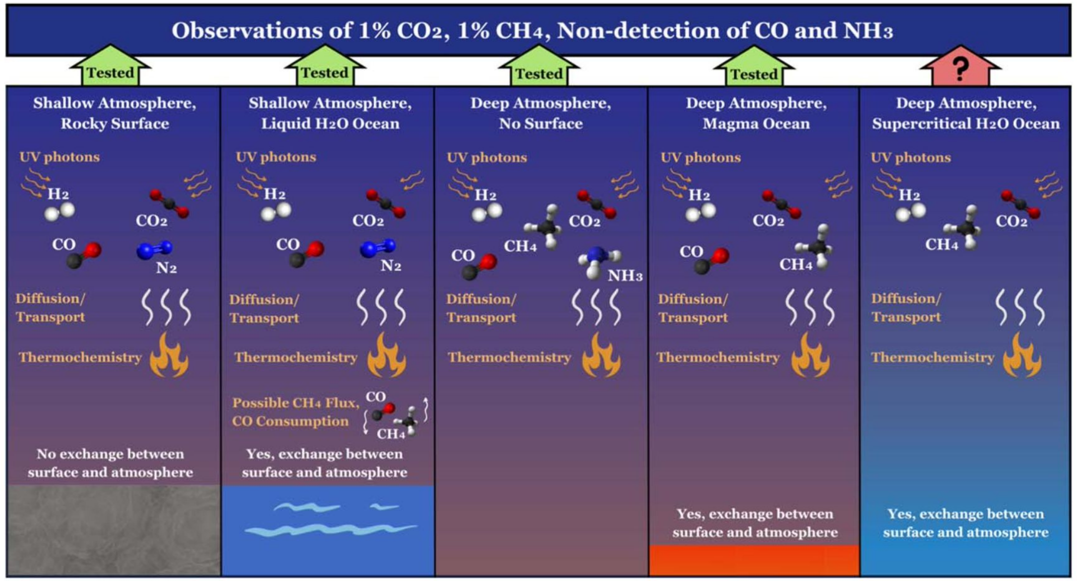



**Figure 1.** Possible conceptual structures for K2-18 b that were explored previously (R. Hu 2021; R. Hu et al. 2021; S.-M. Tsai et al. 2021; X. Yu et al. 2021; N. Madhusudhan et al. 2023b; G. J. Cooke & N. Madhusudhan 2024; F. E. Rigby et al. 2024; O. Shorttle et al. 2024; N. F. Wogan et al. 2024) and in this work.

*Luu et al. 2024 determines a global supercritical ocean can account for the observed $CH_4$:$CO_2$:CO ratios in the atmosphere of exoplanet K2-18b*

**A key question:** How do evolutionary changes in the planetary environment affect the evolution of organic molecules and life? In return, how does life affect the planetary atmosphere, hydrosphere, and lithosphere in observable ways?

**Finding:**
Proposed biosignatures need to be tested with a diversity of abiotic models (e.g., what exotic chemical environments can produce $CH_4$:$CO_2$:$O_2$:CO atmospheric ratios associated with life on Earth? If a supercritical ocean can do this, what signs can we look for to rule out the possibility of a supercritical ocean?)

# Theme 5: Atmosphere and Hydrosphere

*This theme covers the relationship between planets and their host stars*

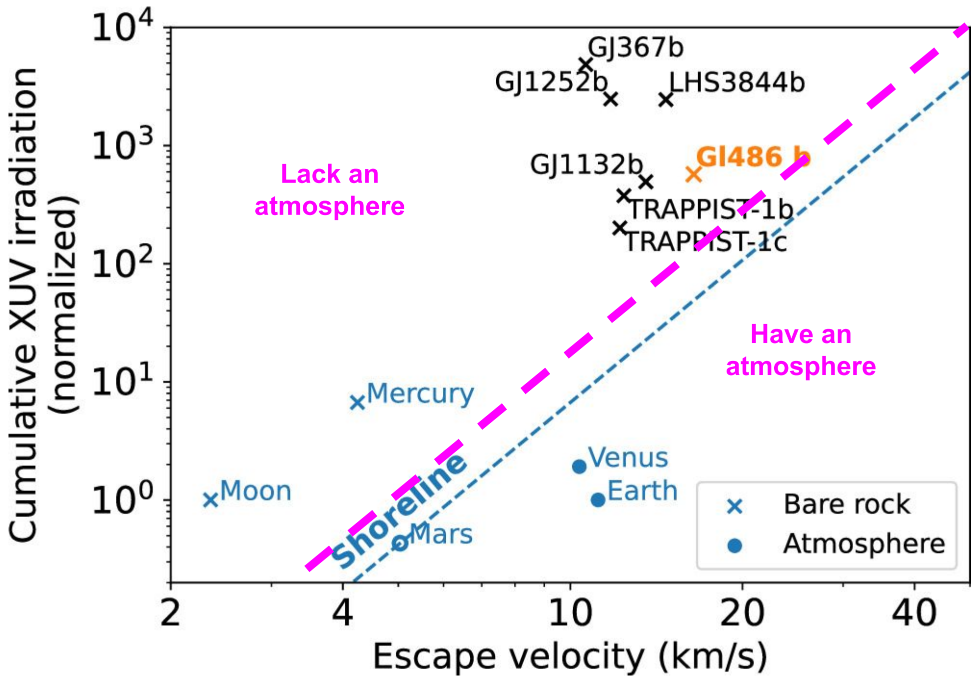
Atmospheric escape is important (MAVEN, the exoplanet radius valley, lack of detected atmospheres on M dwarf small planets thus far…)

Introduction of "Cosmic Shoreline" concept

Increasing appreciation that the exoplanet radius valley is (at least in part) due to atmospheric loss. Direct measurements of atmospheric loss (He, H) from exoplanets help to constrain models.

Constraints on the geochemical evolution of Enceladus' ocean from Cassini plume-flythrough data, and new ideas and improved astrometry for the internal-dynamical co-evolution of Saturn and its moons.

Better knowledge of the temperature and oxygen-content fluctuations of Earth over Gyr (e.g. Catling & Zahnle Science Advances 2020)




*The cosmic shoreline as informed by recent JWST results for exoplanet atmospheres, and models of the time evolution of incident ionizing radiation. From Mansfield et al. ApJL 2024 doi:10.3847/2041-8213/ad8161*

**Findings:**

Host stars are important players in surface habitability. We need to understand combined roles of all energy inputs and planetary parameters

We need need to increase attention to the many other parameters that affect the cosmic shoreline, especially close to the shore

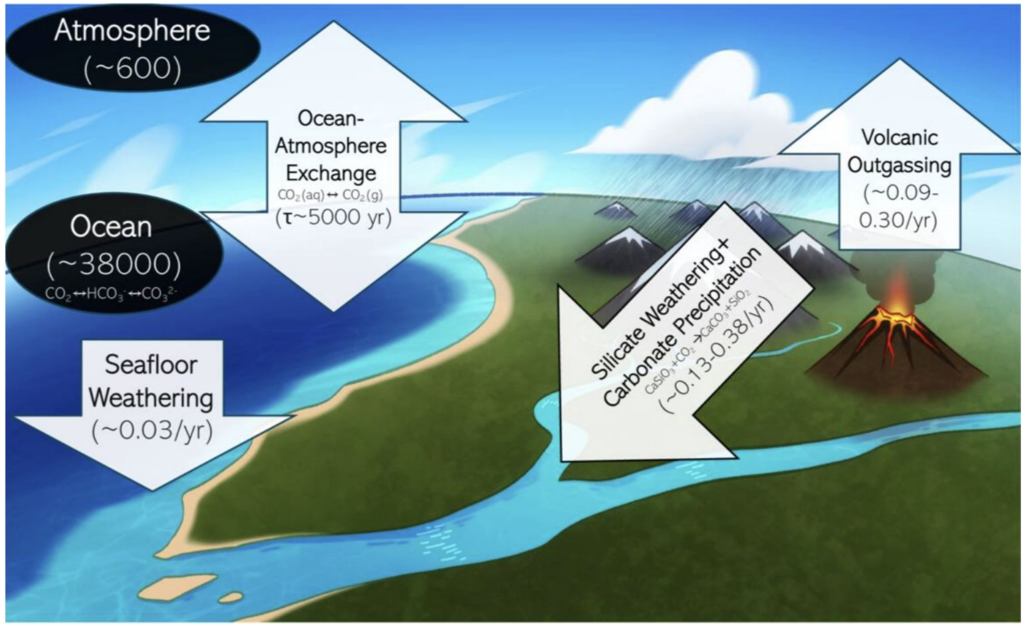
Models of atmospheric escape for high mean molecular weight atmospheres under ultra-high XUV flux are highly valuable.

# Theme 6: System-Level Modeling

Models that track flows between biospheres, atmospheres, lithospheres, hydrospheres, and exospheres - along with the resulting geochemical and environmental changes - are valuable (e.g. Krissansen-Totton et al. ApJ 2022, Halevy & Bachan Science 2017).

There is a need for improved knowledge of planetary material properties at the temperatures and pressures relevant to deep ocean worlds, super-Earths, and sub-Neptunes. For atmospheric escape, there is a need for models of collision-induced opacities and for the emergent XUV fluxes from stars of different spectral types over their lifetimes.

Survivorship bias and chance factors may be a limiting factor in extrapolating Earth-derived models to planets in general (Tyrell et al. Comm Earth Env 2020, Coy et al PSJ 2025)




*There is significant uncertainty in modern-day Earth estimates of reservoirs and fluxes of the slow carbon system. Units: GtC, $10^{12}$kg C. [From Coy et al 2025, doi: 10.3847/PSJ/adf643]*

**Finding**:
Current models of the long term evolution of habitable environments help us understand data, but lack predictive power. This is in part due to the small sample size available to constrain the models. For example, the long-term evolution of Mars' habitability challenges our Earth-derived models of habitability evolution. We do not know why Mars's surface dried up, and we do not know if Mars still has liquid water in the deep subsurface.

What's needed?
For Mars: isotopic constraints from sample return (including but not limited to chronology), whether or not liquid water exists at depth, and climate-evolution constraints from polar ice sampling across stratigraphy. For water worlds: gas solubilities and aqueous chemistry at high pressures. For exoplanets: additional laboratory and numerical experiments on material properties (including miscibility) under the exotic conditions of exoplanets (Kite et al. EoS 2021). For Earth and Earth-like worlds: Comprehensive models tying together core (magnetosphere) - lithosphere - hydrosphere - atmosphere - exosphere to biosphere.

# NASA DARES Focus Area 4

## Comparative Planetology to Understand Habitability

### Focus Area 4 Team

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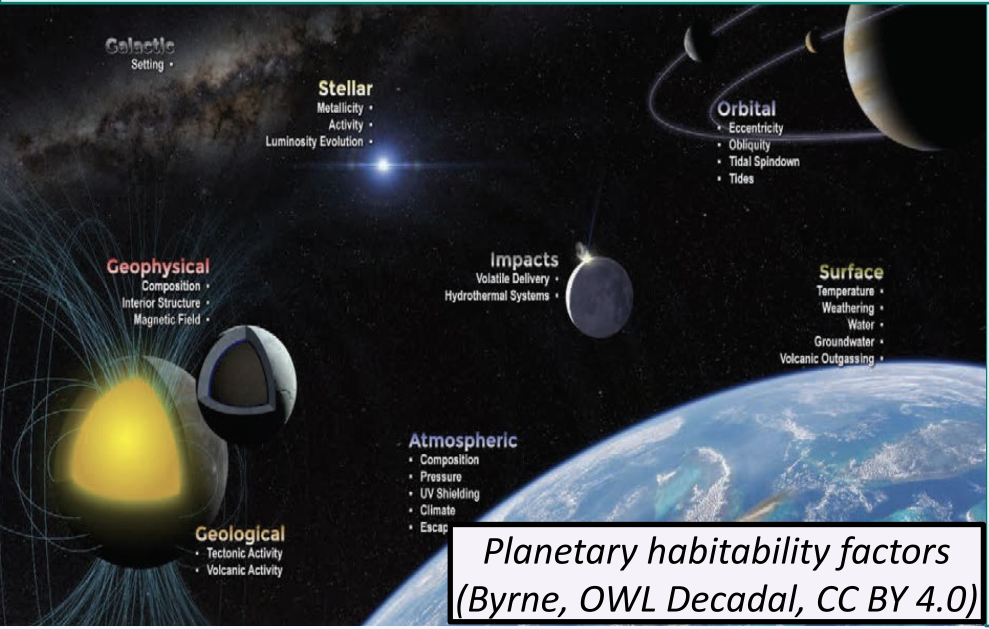
# FA4: Comparative Planetology to Understand Habitability

**FA4 identifies common pathways and boundary conditions for life:** What processes control planetary habitability? Which are universal vs. contingent?



*Planetary habitability factors (Byrne, OWL Decadal, CC BY 4.0)*

## Planetary environments

- Earth
- Ocean worlds & icy moons
- Rocky planets
- Exoplanets
- Small bodies
- Star-planet interactions

## Scientific disciplines

- Geosciences, atmospheric sci., remote sensing
- Organic chemistry, microbiology, ecology
- Astrophysics, stellar & exoplanet sci.

## Core science goals

- Biosignature context
- Quantitative, cross-world habitability frameworks
- Dynamic habitability across time
- Constrain atmospheric evolution
- For missions: ID habitable environments

## Progress since 2015 — comparative planetology milestones

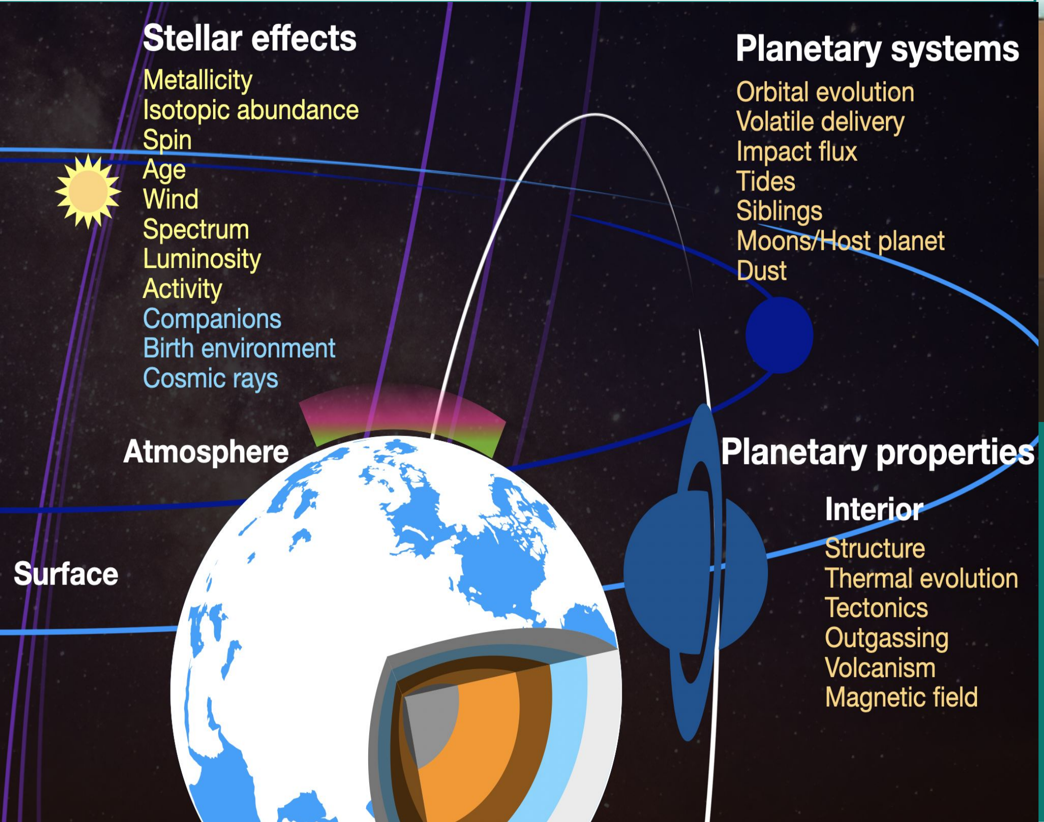
- **2015** Astrobiology Strategy
- **2017** Enceladus $H_2$
- **2020** Bennu carbonate veins
- **2021** Perseverance at Jezero Crater
- **2023** First JWST exoplanet data
- **2024** Europa Clipper launch
- **2025** Cheyava Falls biosignatures?

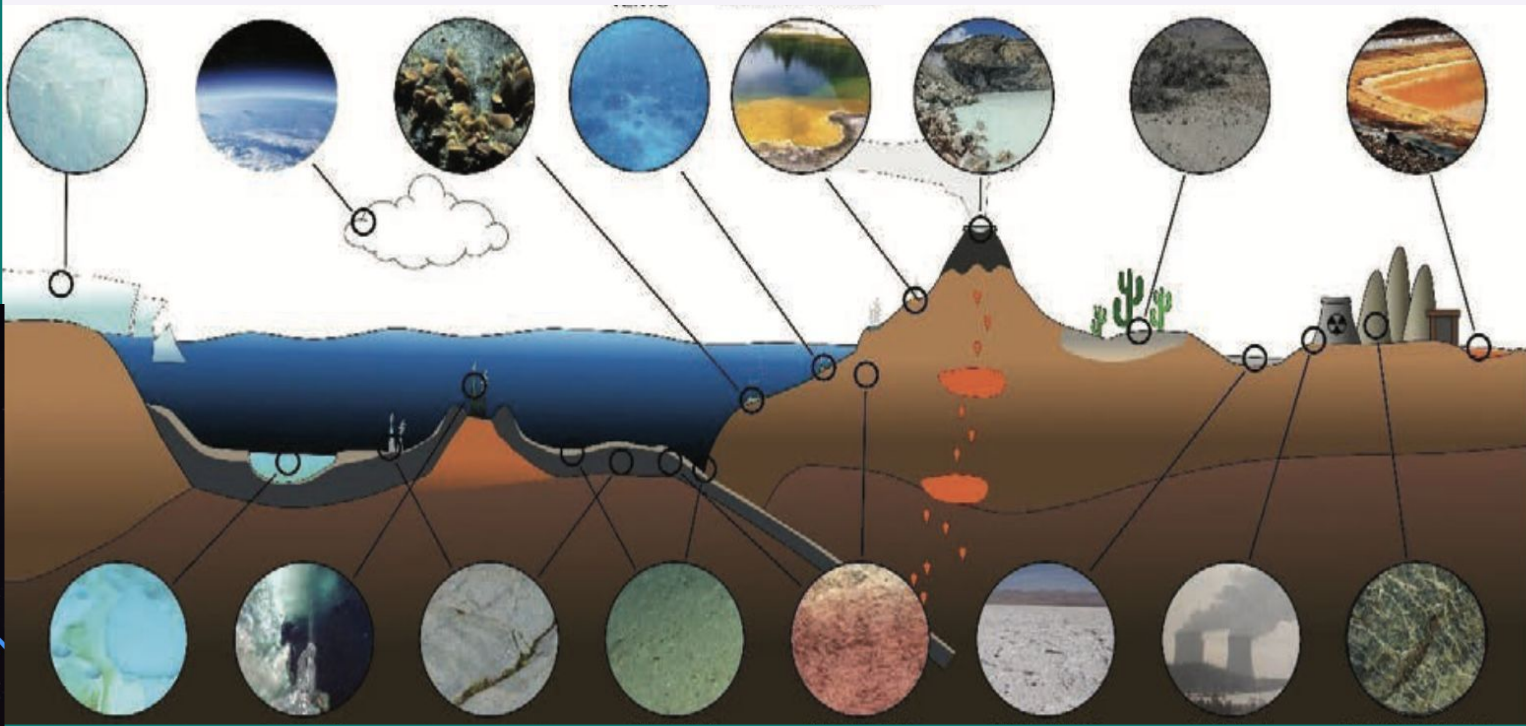
**Why now:** DAVINCI, M2020, Europa Clipper, Dragonfly, JWST, HWO enable system-wide integrative habitability characterization & biosignature searches.

# Overview and Importance

*National Academies context · DARES Focus Area ecosystem · NASA cross-divisional & agency alignment*

**FA4 identifies common pathways and boundary conditions for life using** geological, chemical, and environmental processes across a diversity of worlds.



Merino et al. 2019, CC BY 4.0

**NASA Cross-Divisional & Cross-Directorate Alignment:** Understanding planetary context requires cross-divisional work that can be aligned for field work and mission support while addressing Decadal goals in each SMD division, as well as National Science Foundation.

## Finding 1: <u>Fragmentation</u> across disciplines, infrastructure, and community coordination is limiting comparative planetology progress in astrobiology.

**Comparative planetology would benefit from** creating a centralized hub for information that links to resources currently distributed across NASA divisions, databases, laboratory analog studies, mission datasets, and access to physical infrastructure to enhance the ability to collaborate across subdisciplines.

*Thinkstock*

**Underutilized Research Coordination Networks** (RCNs) could unify community priorities for missions, research, and technology, and improve accountability, akin NASA Assessment Groups (AGs).

*alphaspirit*

**Improved collaboration between mission teams and other astrobiologists** could integrate comparative insight of environmental analogues, ensure astrobiology objectives remain central throughout mission lifecycle, and provide context needed to gauge confidence in life-detection results.

**Successful cross-divisional efforts** (NExSS, NOW, ROSES Habitable Worlds and XRP) could expand to other areas of astrobiology and organize around mission-relevant science gaps, while addressing synergistic Decadal goals in each NASA science division, e.g. Exoplanets in Our Backyard. Workshops, small topical focus conferences, and dedicated cross-divisional funding may enable cross-pollination.

**F1 — Coordination:** What minimum shared data infrastructure, vocabulary standards, and coordination mechanisms are necessary to enable reproducible, NASA-funded cross-divisional comparative planetology?

# Finding 2: "Habitability" is a quantitative, <u>multi-dimensional continuum</u> rather than a binary classification.

We need **quantified standards** for, e.g., habitat suitability, biological potential, biosignature potential, carrying capacity, biomass, productivity, sustained habitability.

**Quantitative reference frames for assessment:**

1. **spatial scale**: planetary body, regional, microenvironment
2. **time scale**: instantaneous vs. geologic
3. **life reference frame**, e.g., Earth biosphere, chemolithotrophy, life as we don't know it

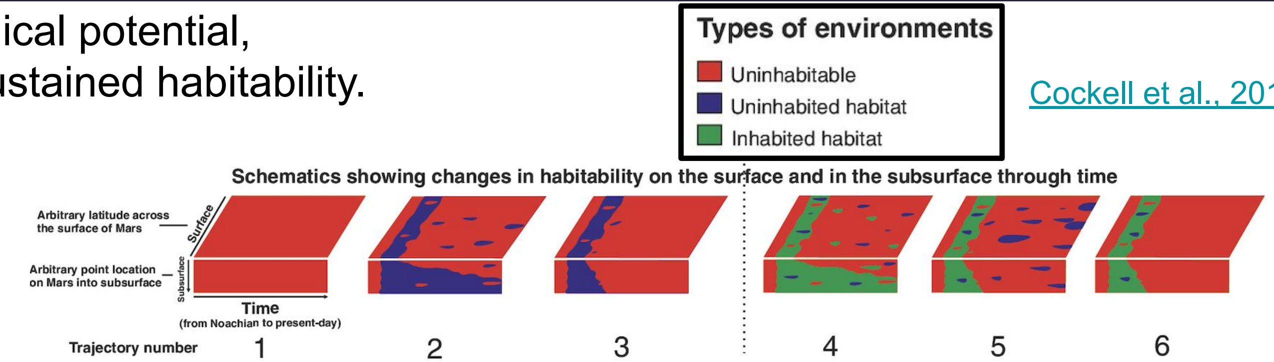
Leverage **ecological framework** models.

**Biosignature context science**, including star characterization, photochemistry, planetary evolution, and abiotic pathway modeling, is needed alongside biosignature detection science.

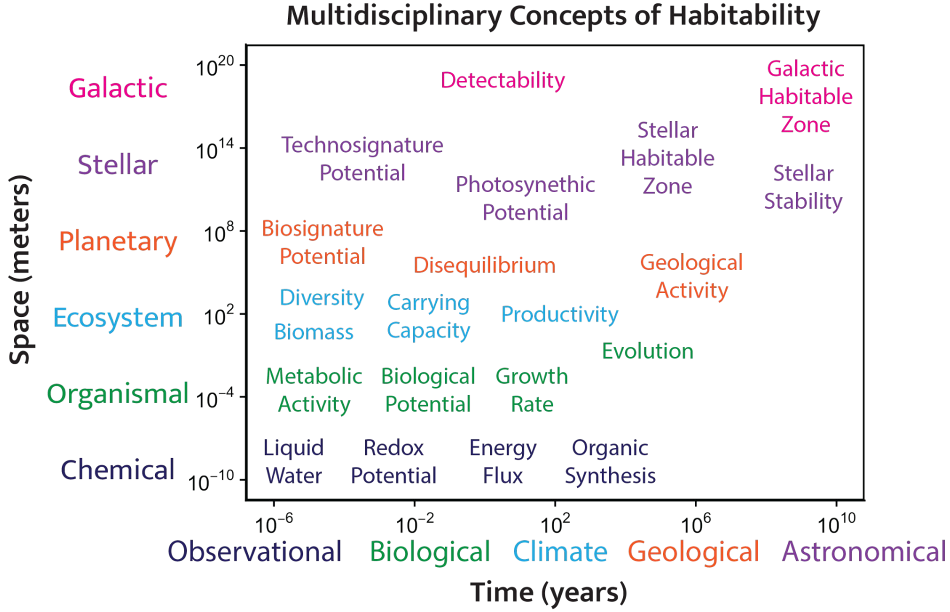
**Habitable-but-lifeless environments** constrain life's inevitability.

**Incorporate dynamic and transient habitability** into frameworks alongside stable, long-term assessments.

Understanding **how organics modify chemical environments** bridges prebiotic chemistry and biological systems, and is essential to building robust frameworks.




Cockell et al., 2016



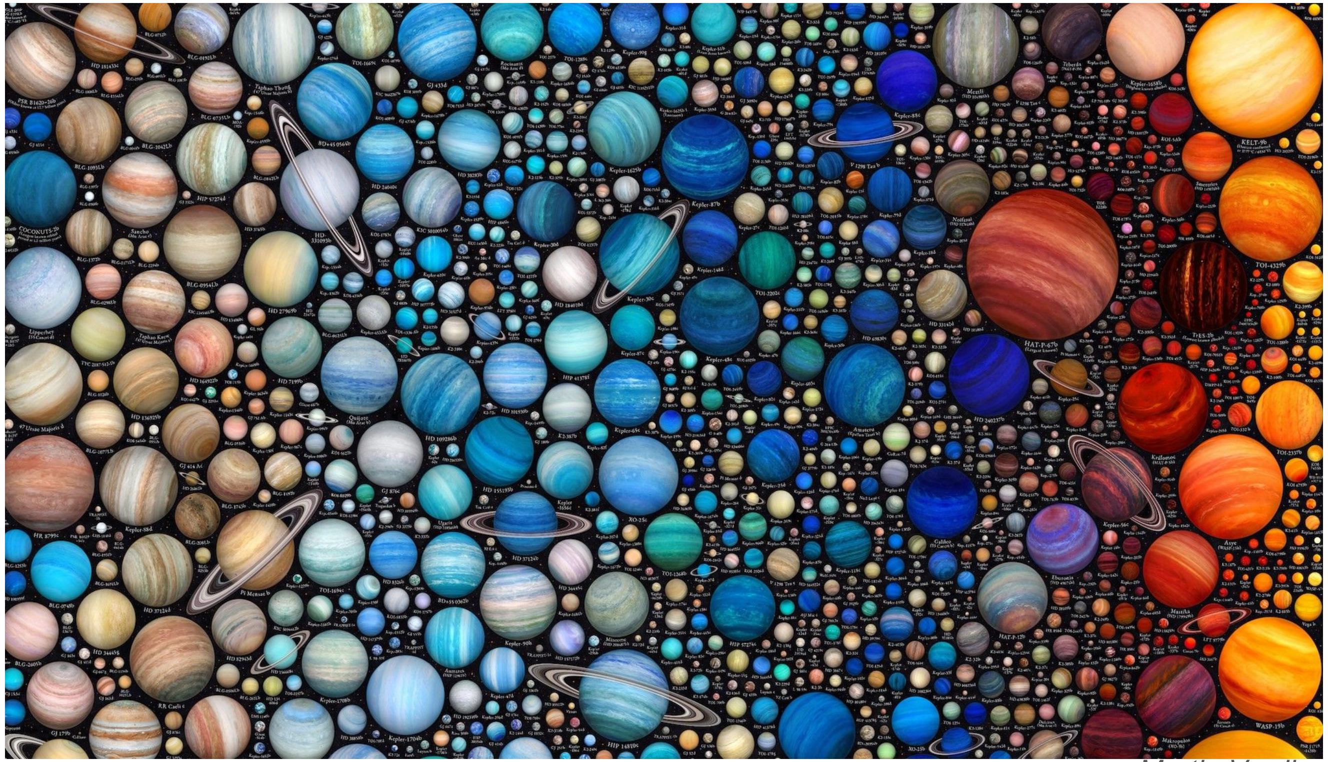

**F2 — Habitability metrics:** Can we define a quantitative habitability framework — one that specifies scale, timescale, and life reference frame — that is operationally useful across solar system and exoplanet contexts? How would abiotic organic inventories affect that framework?

# FA4: Comparative Planetology to Understand Habitability

## Finding 3: Developing a <u>two-way synergy between Solar System and exoplanet research</u> maximizes scientific return.

JWST, HWO, and ground-based observatories will survey **trends in planetary evolution** across diverse stellar and planetary parameters. Contextual understanding of the Earth through time, Venus, Mars, ocean worlds, the Moon, and Ceres is critical to understanding the signals broadcast by potentially habitable exoplanets.

Half of the exoplanetary systems HWO will image are **older than the solar system**, some >10 Gyr. Modeling future planetary states, including Earth's, will guide HWO observations and interpretation of their results.



*Martin Vardic*

**Geosignatures bridge Solar System and exoplanet science.** The deep-time record of Earth and other planetary bodies provides a comparative foundation to interpret exoplanet observations.

**F3 — Solar system / exoplanet bridge:** How do the habitability trajectories of solar system worlds — including future states of Earth — constrain the interpretation of exoplanet atmospheres and surfaces observed by JWST and HWO?

## Finding 4: <u>Earth is a unique but limited</u> comparative planetology reference; process analogs, deep-time records, and other planetary bodies are essential complements.

Earth's diversity of environments and accessibility to investigations at microbial to planetary scales make it a unique asset to comparative planetology. Biological overprint and geologic record gaps on Earth warrant complementary exploration of other worlds with no detectable life and less geologic activity.

Field analogs on Earth for Mars, Venus, ocean worlds, cryospheres, caves, and dunes are better understood as **process analogs rather than perfect physical analogs**.

Earth's evolving habitability from the Hadean onward constitutes a comparative sequence in itself to study geosignatures as context for biosignatures.

**Earth remote sensing missions are an opportunity** to learn about remote observations of life-bearing environments.

**The Moon and other planetary bodies hold clues to Earth's history** and the conditions sustaining life's origin and evolution.

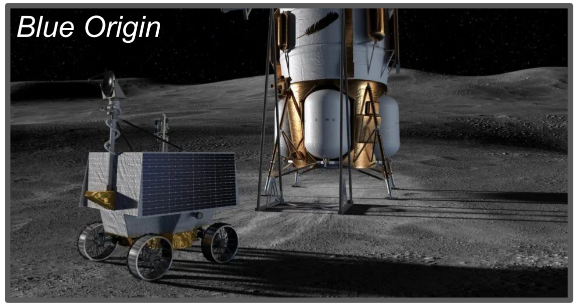

*Carl Conway/ Springer Nature Limited*

**F4 — Earth as analog:** To what extent can Earth's deep-time record serve as a template for detecting planetary-scale abiotic signatures (geosignatures) on other worlds, and where does it fail as a process analog?

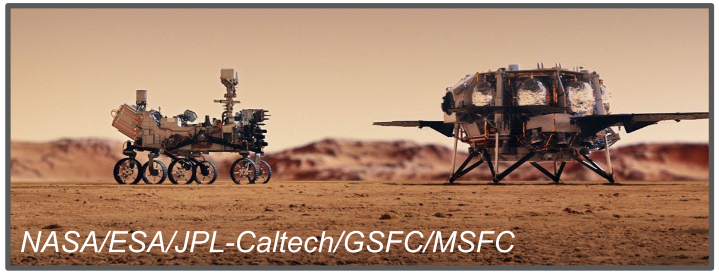
# FA4: Comparative Planetology to Understand Habitability

## Finding 5: Investment in field programs and mission continuity is essential to comparative planetology.

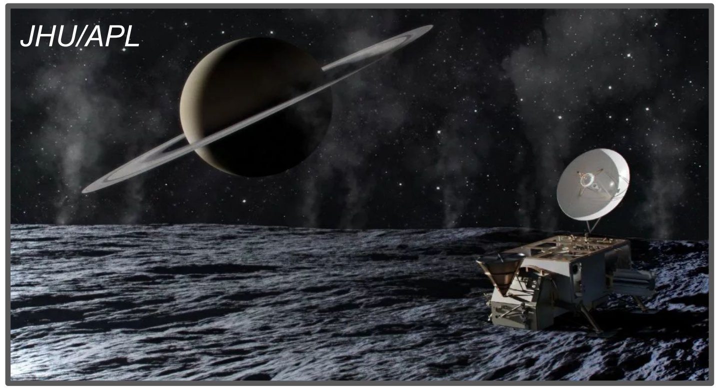
**Support for field work has declined**. Antarctica is out of reach of many SMD solicitations. A course reversal to fund access for ethical work at process-analog sites for Mars, Venus, and ocean worlds, at a fraction of the cost of robotic missions, would solidify of the design, operation, and interpretation of mission data.




**Low-habitability environments on Earth are important planetary analog sites** (e.g. caves, atmospheres, etc). Organic-poor permafrost habitability on Earth remains poorly constrained, a notable gap for Mars Life Explorer and human exploration, ripe for investment by NASA Earth Science, Planetary Science, and Human Exploration.




Rapid-cadence **lunar missions are an underutilized astrobiological opportunity.** The Moon represents a potential field site. Because it is uninhabitable, it could preserve samples of early Earth and other planets, record other infalls, and allow study of human-induced habitability on decadal timescales. The Moon offers a chance to study the evolution and dynamics of crust+ mantle system distinct from Earth.




**Field work is essential because tension exists, exacerbated by low mission cadence**, between broadly robotically surveying potentially habitable locales and deeply investigating the most accessible targets. Dedicated field sites may expand research access. Prioritization and support for high-priority mission concepts are key.

**Venus** is key to understanding Earth's evolution in both Solar System and exoplanetary contexts; DAVINCI and VERITAS are key to sustaining progress.

**F5 — Field and mission strategy:** Which field programs and mission targets offer the highest leverage for constraining the boundaries of habitability under current mission cadence constraints?

# NASA DARES Focus Area 5

## Detecting Signs of Living Environments and Living Worlds

### Focus Area 5 Team

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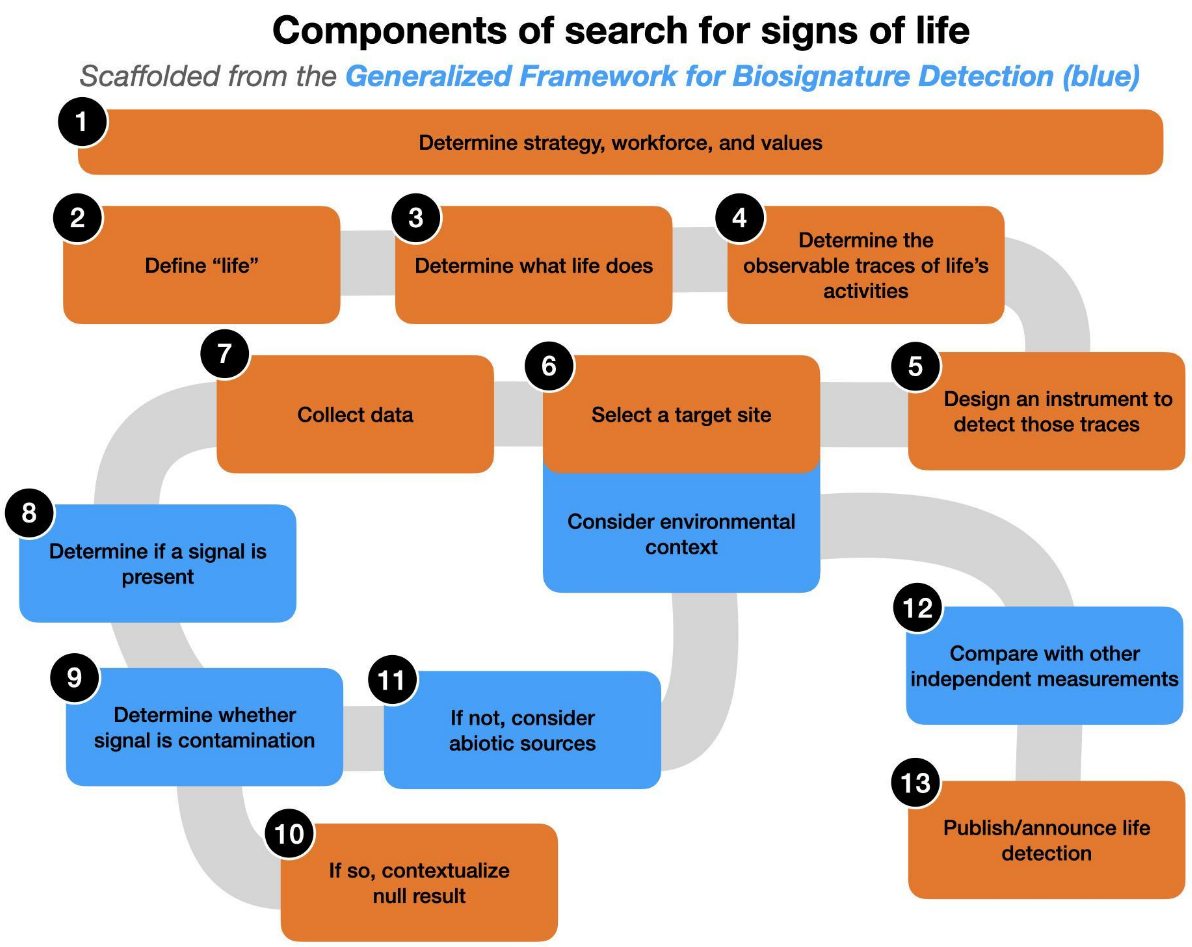
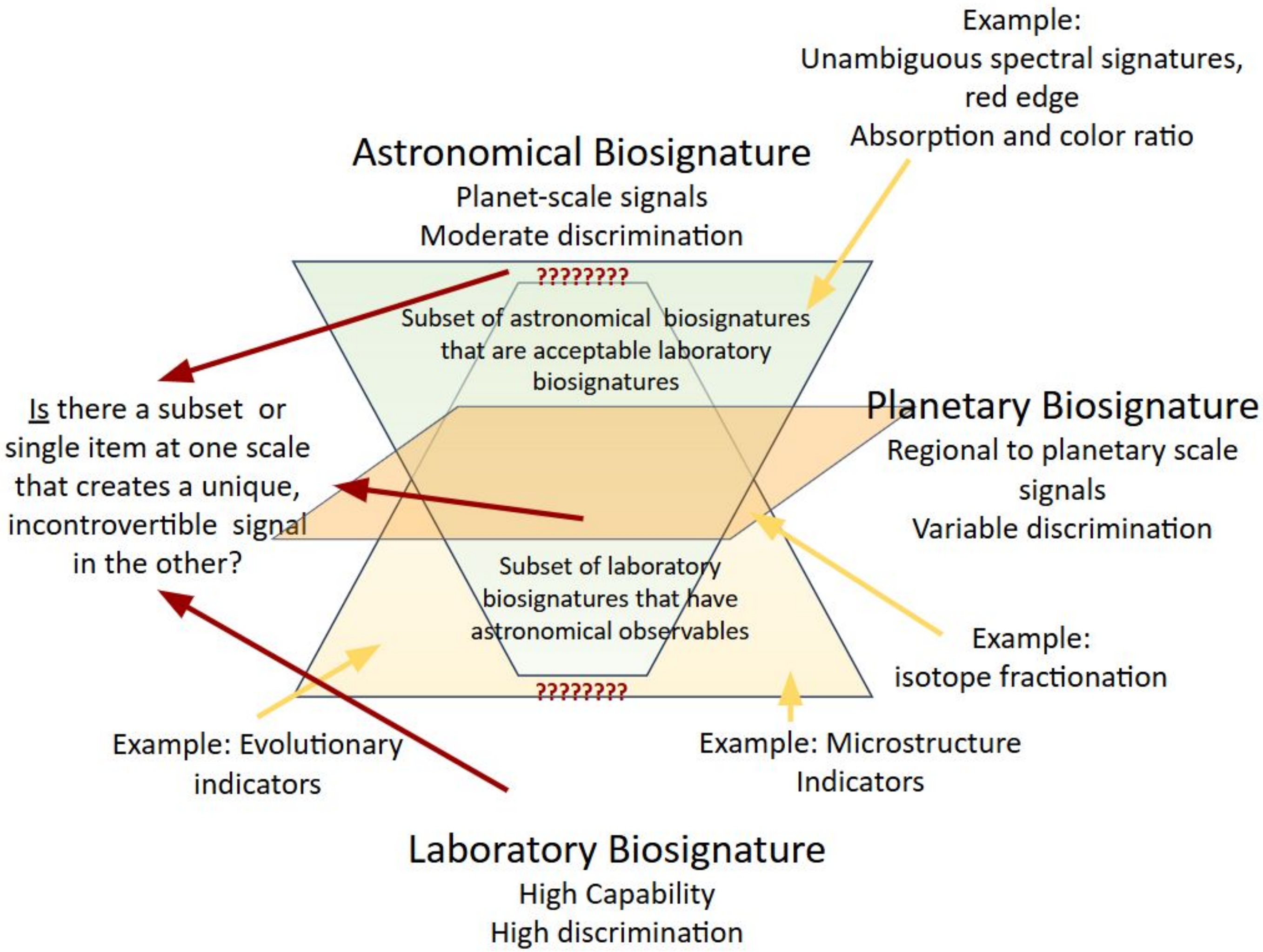
- Tiffany Kataria, Ph.D.
- Noam Izenberg, Ph.D.
- Bonnie Teece, Ph.D.
- Mary Beth Wilhelm, Ph.D. *(NASA Ex-officio Member)*




This Focus Area spotlights the need to continue refining our approach to detecting signs of life on other planets inside and outside our solar system.

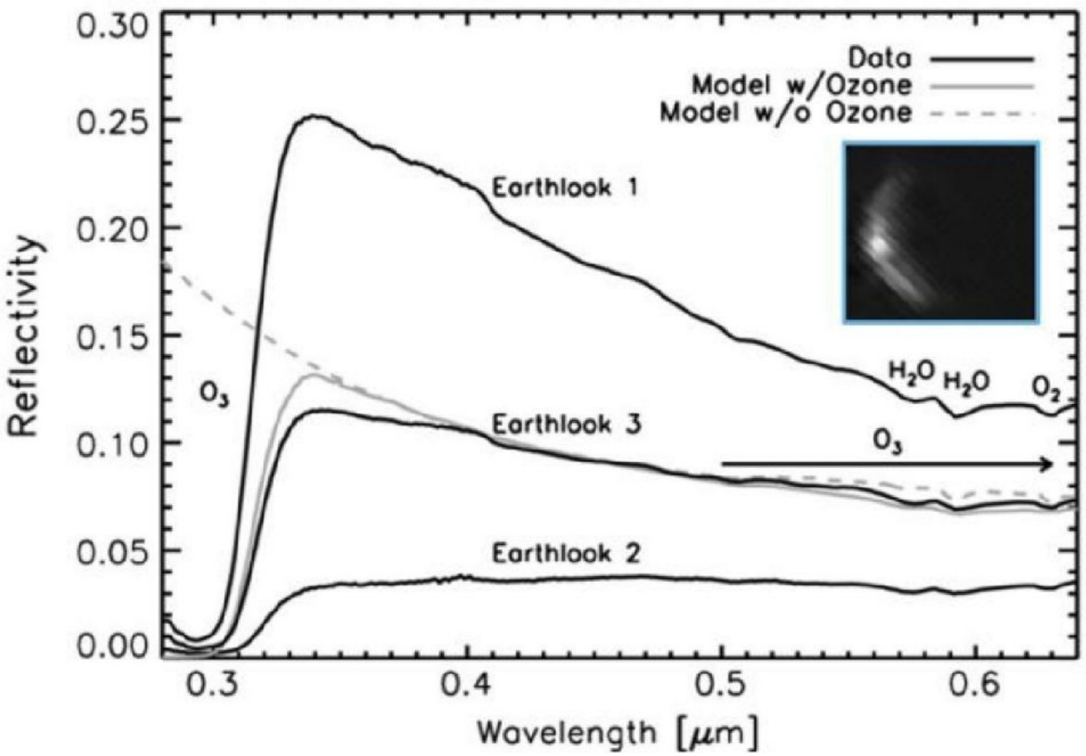
## Topics Covered

- **Planetary Atmospheres: Exoplanets and our Solar System**
- **Co-Evolution of Biosignatures and Worlds**
- **Technosignatures**
- **Atmospheres, Hydrospheres, and Biosphere: Planetary Co-Evolution**
- **Biosignatures in our Solar System**




**Finding #1: Definitions of foundational terms like "habitability" and "biosignature" are context and scale dependent. The community should take care to define these terms when they are used in interdisciplinary groups and further work may be needed to develop a truly universal definition.**

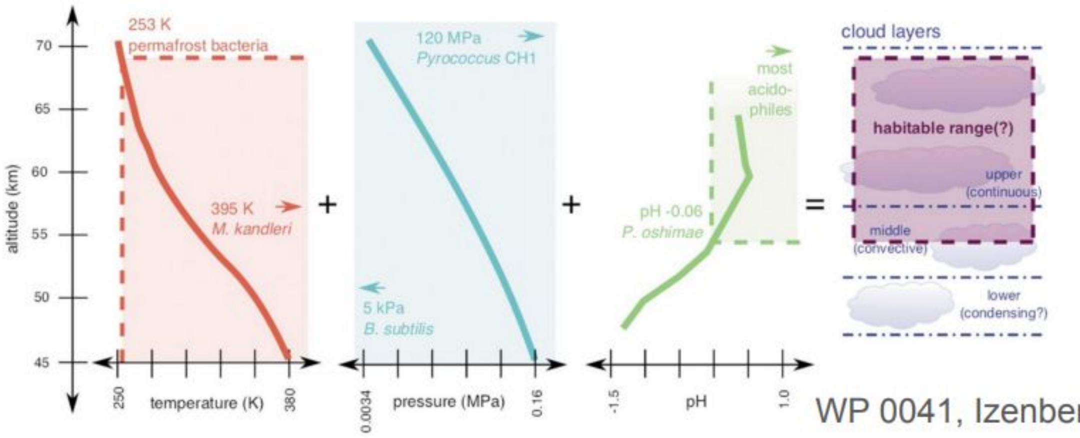
- Include a working definition as the output of a work product and the ground rules for any documents and meetings.



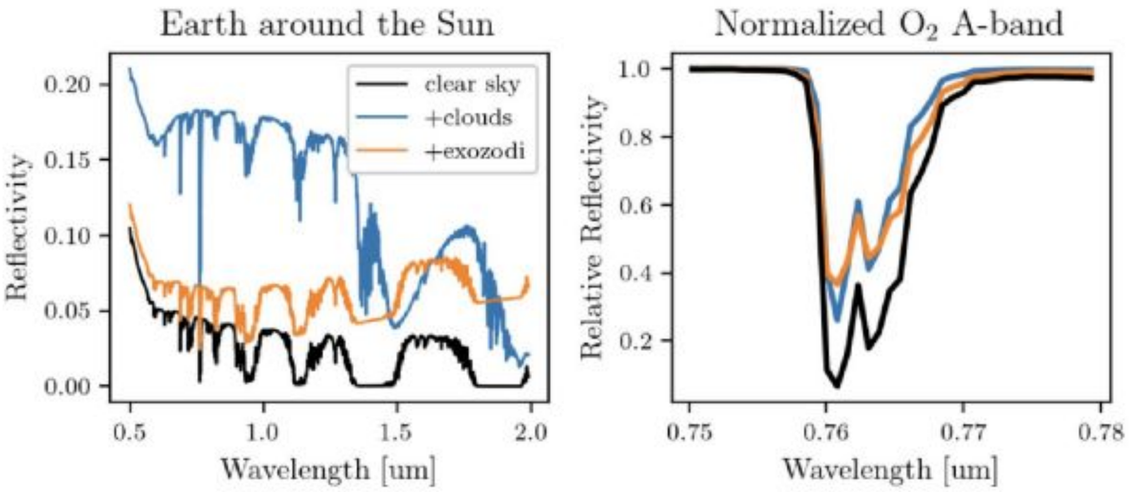

WP 0095, Meadows+

**Finding #2: Exoplanet science has matured to the point that it can bidirectionally inform and be informed by atmospheric and surface biosignatures searches in the solar system. [NAS: OWL2023, ASTRO2020, EXO2018; NASA: ASTROBIO2015]**

- A lot of progress has been made, but many astrobiologists require additional training and resources to increase meaningful collaboration between in situ and and exoplanet studies. Further work is needed to integrate this community into the larger astrobiology framework.
- Statistics from exoplanet surveys can be used to support, validate, and contextualize solar system biosignatures.
- Exoplanet studies tests extremes, which can inform our overall physical understanding of environments in our solar system.
- Laboratory-measured line lists and opacities for gases and surface signatures of interest are needed.



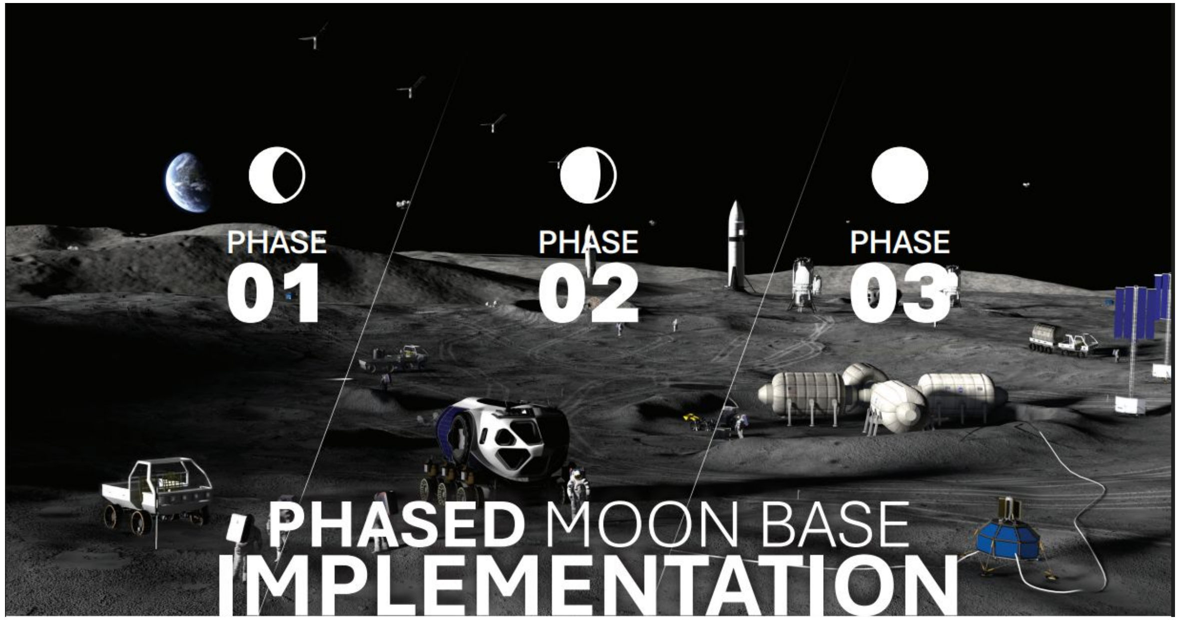

WP 0041, Izenberg+




WP 0034, M.Currie+

**Finding #3: Planets and their host stars are a collection of complex time-dependent systems which must be studied holistically to understand expected biosignatures, and their preservation and presentation through deep time [NAS:MARS2026, OWL2023, ASTRO2020, EARTH2018, EXO2018; NASA: ASTROBIO2015, MEP2024, M2M2025]**

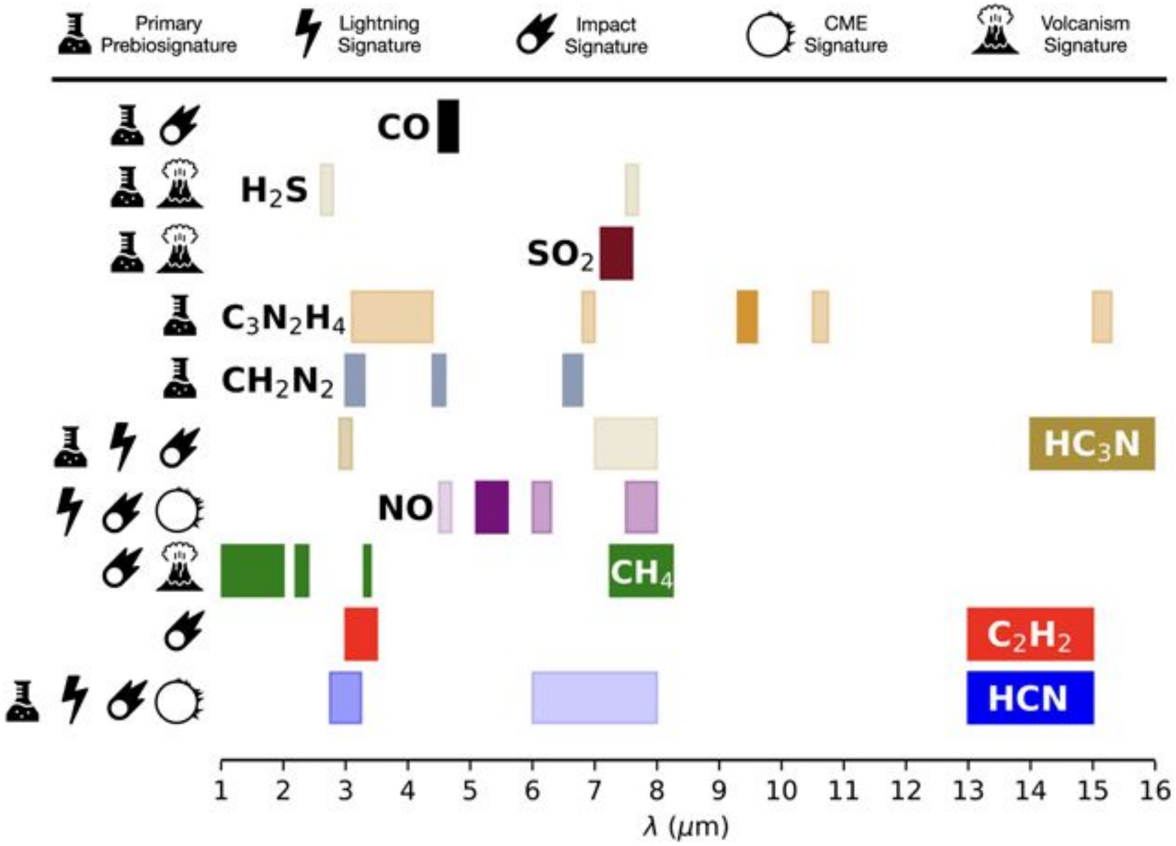
- Improved modeling of atmospheric escape across stellar types is needed.
- Consider non-photosynthetic biosignatures in the atmosphere, hydrosphere, lithosphere, and cryosphere (e.g. trace gas oxidation) in terrestrial analogs and extra-solar exploration.
- Earth through geologic time can be an analog for multiple different target bodies. Physical space (e.g. stratigraphic depth) can and should be used as a proxy for time.
- Thorough characterization of planetary systems is necessary to interpret potential abiotic sources reducing the risk of detecting false positives.




https://www.nasa.gov/wp-content/uploads/2026/04/moon-base-architecture-users-guide.pdf

**Finding #4: Existing and future Earth, planetary, and space science missions and programs should better integrate cross-divisional research in astrobiology and the search for life. [NAS: OWL2023, EXO2018; NASA: ASTROBIO2015, MEP2024, M2M2025]**

- More collaboration is needed between government, academic, and commercial spheres. NASA-led launches are far apart and technology development cycles are slow. In industry, launches are more frequent and prototype iterations are faster. One example of cooperation could be instrumentation incubator/accelerator programs with higher risk tolerance.




Claringbold et al., 2023

**Finding #5: We should better characterize the abiotic background to enable scientists to robustly report a detection of alien life. [NAS:MARS2026, OWL2023, ASTRO2020, EXO2018; NASA: ASTROBIO2015]**

- The abiotic baseline is poorly characterized— the chemistry, concentrations, and distribution expected from purely abiotic processes haven't yet been synthesized into a usable reference framework and will be essential to interpreting a mixed signal.
- Null results constrain our search space and are critical for astrobiology, and must be interpreted thoughtfully with consideration of false negatives.
- Biosignature standards are applied differently inside and outside the solar system.

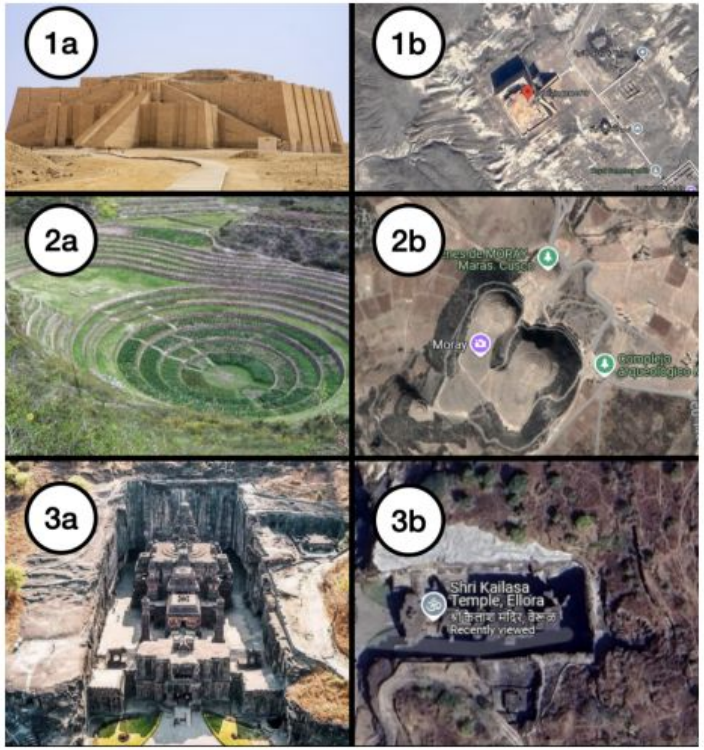
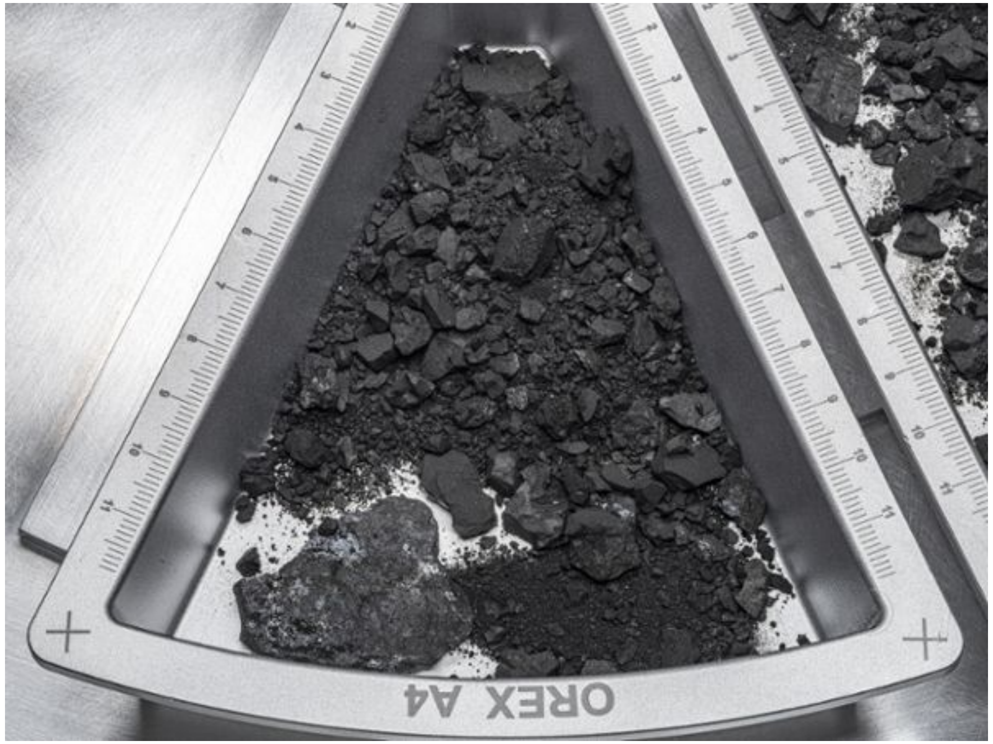



Figure 1: Three examples of surface technosignatures on Earth that are over 500 years old and are visible in orbital satellite imagery: 1) Ziggurat of Ur 2) Inca Agricultural Terraces and 3) Kailasa Temple. The a) images show the structures from a near-surface perspective while the b) images are representative of the structures appearance in satellite imagery, as sourced from Google Maps. Two takeaways can be drawn here: surface technosignatures can be readily identified from satellite imagery, and we have a large, consistent training dataset of examples of human surface technosignatures from the Earth itself.

WP 0038, Henrique+

**Finding #6: Technosignature research has diversified and advanced substantially since the last Astrobiology Strategy in 2015 and should be better incorporated in biosignature research. [NAS:ASTRO2020; NASA: ASTROBIO2015]**

- Technosignatures are part of a robust astrobiology portfolio and may be particularly useful signatures of life to search for due to their relative lack of natural false positives and/or potential longevity
- Technosignatures could manifest across the EM spectrum and across astronomical environments (e.g., surfaces, atmospheres, orbital environments)
- Science traceability matrices for missions utilizing radio and optical wavelength measurements should include technosignatures.
- The Habitable Worlds Observatory is critical for both atmospheric biosignature and technosignature investigations.
- Laboratory-measured line lists and opacities for technosignature gases and surface signatures are also critical
- Technosignature research has significant gaps in institutional support and previous strategic documents and warrants increased attention (e.g. OWL 2023).



Lauretta and Connolly et al., 2024

## Finding #7: Sample return remains a critical component of a robust astrobiology strategy. [NAS:MARS2026, OWL2023; NASA: ASTROBIO2015, MEP2024, M2M2025]

- Many sample analyses cannot be performed outside of terrestrial lab facilities, and this will remain true for the foreseeable future, so sample return missions reduce the risk of false negatives.

# NASA DARES Focus Area 6

## Astrobiology-Focused Mission Approaches and Technology Development

### Focus Area 6 Team

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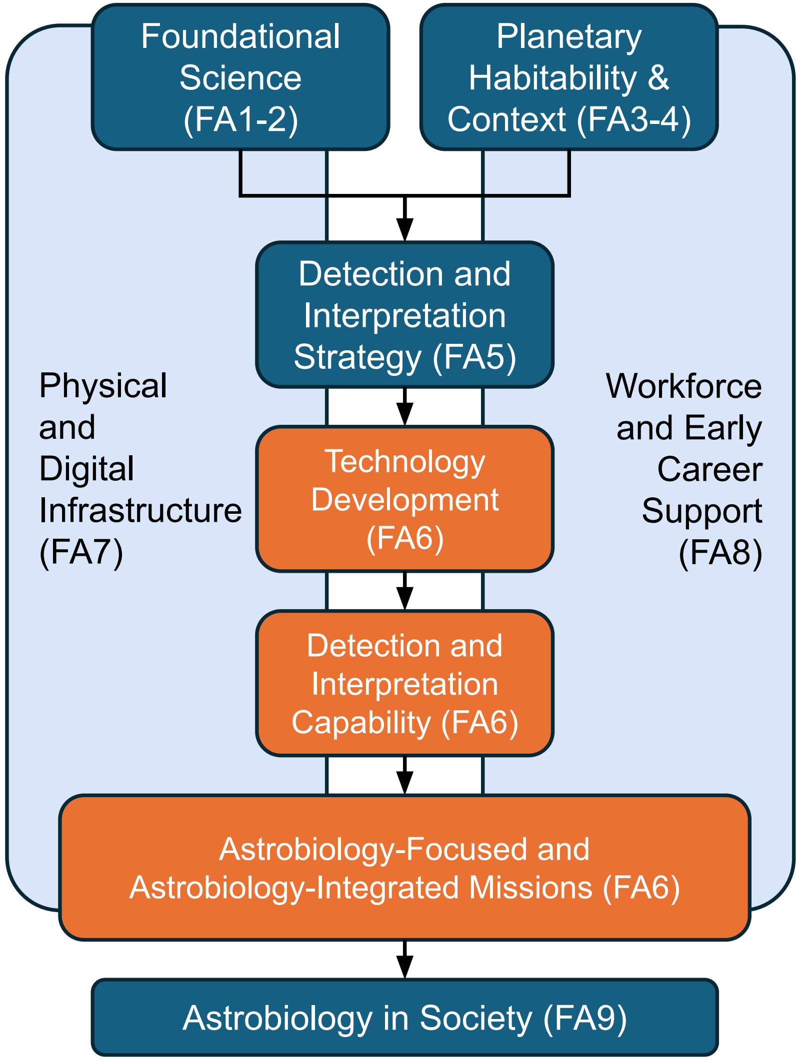
- Christopher Carr, Ph.D.
- Kate Craft, Ph.D.
- Brian Glass, Ph.D.
- Bonnie Teece, Ph.D.
- Niki Parenteau, Ph.D. *(NASA Ex-officio Member)*

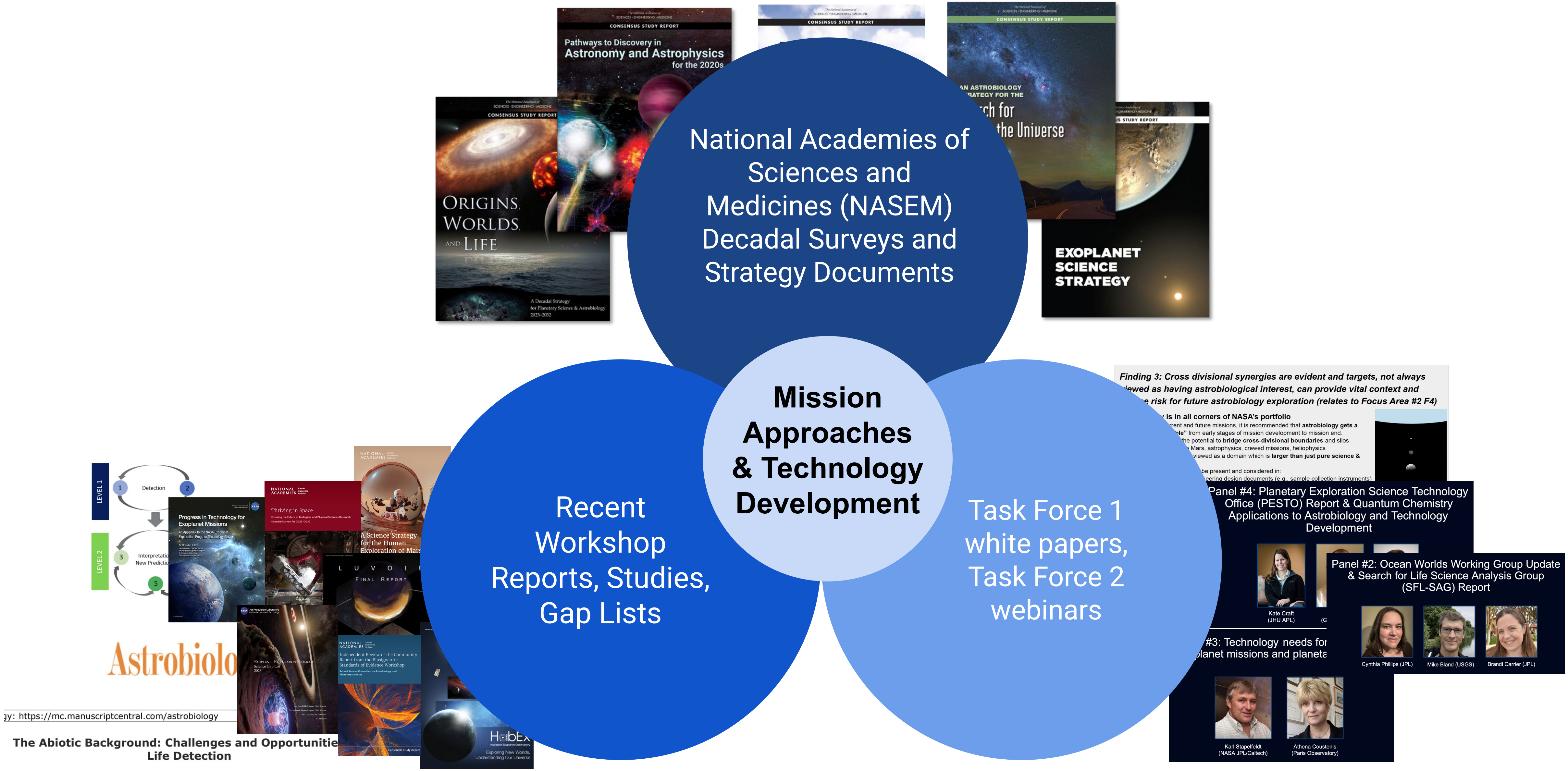
# Overview

- We seek to translate research on biosignature detection and interpretation within the context of the environment into **measurement requirements and robust, adaptable strategies** for astrobiology missions.
- Our science (and our ability to answer astrobiology-focused questions) is inherently constrained and defined by the **integrated payloads and the samples we select** to analyze, or **remote/telescopic observations** we choose to perform.
- Strategic advancement of **key technologies** and implementation of astrobiology-focused **mission approaches** will be enabling for future investigations.
- Findings are driven by the 'search for life,' and while some may be target-specific or mission implementation-specific (e.g., remotely detectable vs *in situ*), **astrobiology is broadly applicable and requires coordination across many mission types** over multiple Divisions within the Science Mission Directorate.

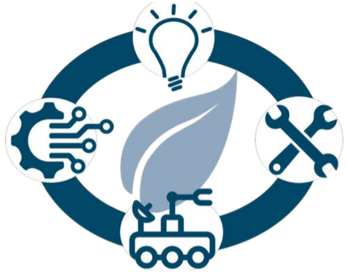


# FA6: Astrobiology-Focused Mission Approaches and Technology Development

Findings are **rooted in the NASEM Decadal Surveys** and build on the 2015 Strategy



# Mission Approaches and Technologies: Draft Findings



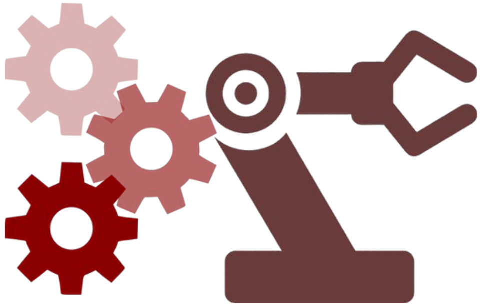
**Astrobiology requirements should be incorporated across all mission stages,** from inception and conceptualization, to planning, development, design, fabrication, contamination control, launch and operations, as well as data analysis and interpretation.

- **Mission precursor and preparatory science should be coordinated across all of the Science Mission Directorates** (Planetary, Astrophysics, Earth Science, Heliophysics, Biological and Physical Sciences).
- **All prior and future instrument datasets should be modernized to improve access by humans and AI agents** to facilitate interpretation, reuse, and further development.

**We are entering a new landscape of planetary exploration with greater involvement of missions developed by other nations as well as the private sector, and increased potential for human exploration.** Coordinated efforts between all parties to facilitate safe and sustainable planetary exploration will particularly benefit astrobiology-focused missions, as these tend to have the most stringent planetary protection requirements.

- **Envisioned and new missions will further expand the need for planetary protection processes, their validation, and evolution**, including integration of human and robotic exploration.
- **Human space exploration needs to include both forward and backward contamination avoidance protocols with the appropriate technologies and hardware**. Lunar missions could be excellent opportunities to test in these areas.

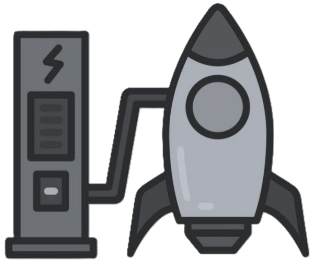
# Mission Approaches and Technologies: Draft Findings



**Astrobiology-focused** planetary and astrophysics mission architectures would benefit from **diverse and better integrated sampling and instrument measurement strategies** that take advantage of improved sampling access, comprehensive/coordinated sampling systems, integrated instrument suites, and analysis tools developed through **sustained programmatic support.**

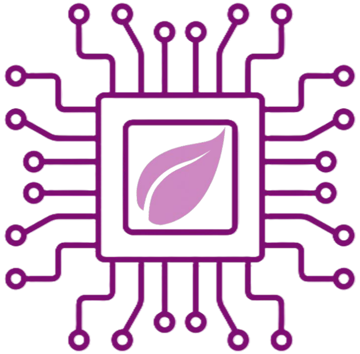
- **Access to multiple sampling locations (with minimal processing/contamination and/or that are well-characterized) across space and time is a key driver** for *in situ* life detection missions. For certain mission architectures, different scales of **mobility is a means to manage our relative lack of knowledge of astrobiology targets**.
- **The development of integrated instrument suites and optimization of mission architectures can be accelerated and supported by use of standard interfaces, standard sample reference suites, and integrated modeling to optimize science return** (e.g., AI/ML and quantum chemistry). For *in situ* astrobiology missions, these instrument suites should be tested in analog environments, and fully developed addressing **planetary protection and cross-contamination issues.**
- **Future life detection missions require sustained instrument development programs across TRLs that support both general and specific mission needs.** For example, *in situ* astrobiology missions require maturation of sample collection and processing instrumentation (we propose a new program: SampleTech). Astrophysics missions searching for signs of habitability and life require sustained development of e.g., conventional and emerging coronagraph technologies (see the Exoplanet Exploration Program Science and Technology Gap Lists).
- **Sample return missions have different technology needs than in situ missions.** Programs to support technology development should recognise this, not just focusing on TRL but improving capabilities here on Earth, to minimise sample usage and maximise science return.

# Mission Approaches and Technologies: Draft Findings



New capabilities in **power, propulsion, autonomy and servicing** may indicate that different missions and approaches not previously envisioned may be feasible, which would enhance the science return of astrobiology-focused missions.

- **New emerging capabilities** such as large mass to orbit, fission power, and other types of propulsion which go beyond traditional assumptions around mass, power, volume, capability **are enabling for access to the outer planets.** Servicing of telescope missions would allow for inclusion of next-generation instruments to extend astrobiology capabilities.
- **Autonomy can and should be incorporated in current and future astrobiology-focused planetary and astrophysics missions.** This will likely include mission operations, sampling decisions based on discovery to optimize opportunistic science, anomaly detection, data processing, and autonomous laboratories.



Astrobiology-focused missions should be designed to **"interpret the potential biosignatures within the context of the environment"** and should use frameworks designed to vet potential biosignatures within a **false positive and false negative framework,** built on Science Traceability Matrices (e.g., the Life Detection Knowledge Base) and informed by 'after the fact' frameworks for assessing returned data (e.g., the Biosignature Standards of Evidence).

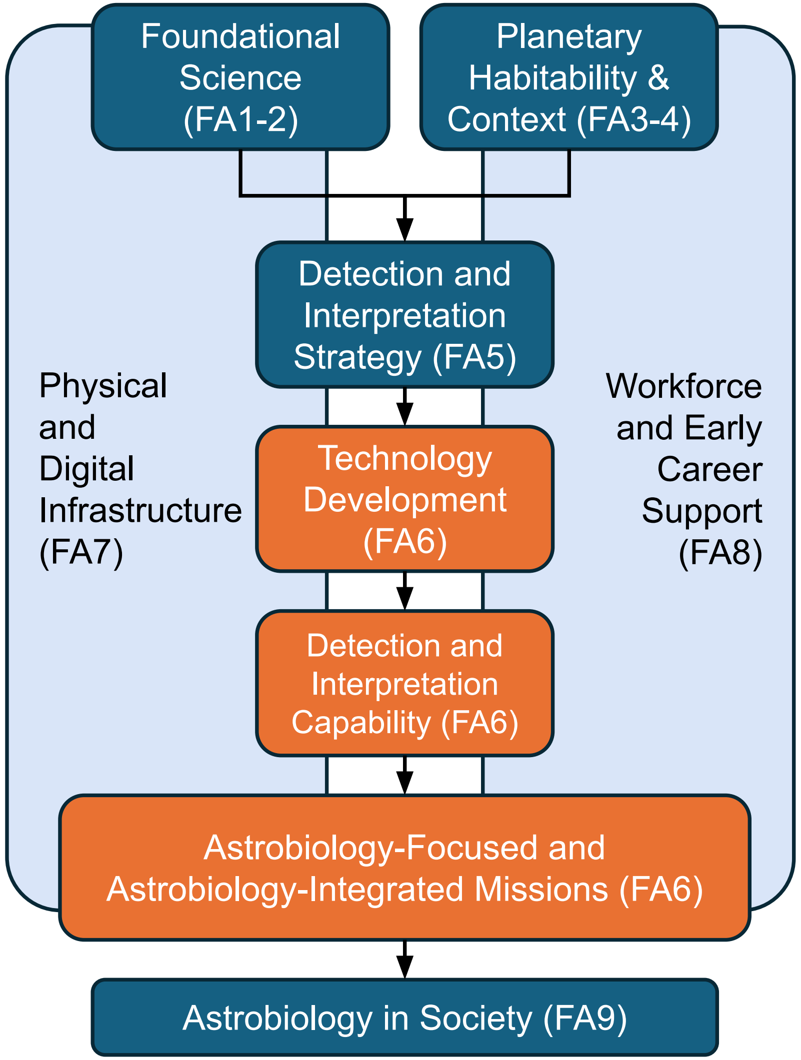
# Mission Approaches and Technologies: Draft Findings

New findings that expand our repertoire of astrobiologically-relevant targets demands **development of adaptable mission architectures and technologies** to accommodate **wider chemical and physical environments.**

- **Organic chemistry in nonaqueous solvents** and other chemical conditions present in environments throughout the solar system and potentially on exoplanets may require non-traditional and/or adaptable approaches to sample handling and analysis.
- **Challenging physical environments** also drive new strategies for sample collection and processing. For example, while high pressures of deep oceans should be prioritized, recent results show us that asteroidal parent bodies previously considered as abiotic may once have been ocean worlds with the potential for prebiotic chemistry or even life. These new environments present physical challenges on the opposite spectrum, such as sampling in very low gravity.

# Connections to Other Focus Areas

- **Science drives** the technology, detection and interpretation capabilities necessary for astrobiology-focused and integrated missions **(FA1-5)**.
- **Technology Development and Mission Implementation** will benefit from broader availability of samples and validated components, subsystems, instruments, and interfaces **(FA7)**.
- **Workforce (FA8)**
  - Stable funding across the technology readiness continuum is essential to enabling long-time-horizon capabilities and develop the workforce.
  - Challenging to 'break in' to mission work. Some funding programs exist (e.g., Europa ICONS, Dragonfly Guest Investigator Program, Planetary Science Summer School, Mission Ideation Factory) but they are very oversubscribed and often only target early career investigators.
  - Opportunities can be created to develop operational expertise through staged learning/risk models.
- Missions are an essential vehicle through which we provide **critical grounding to our understanding and interpretation** of our place in the Universe **(FA9)**.



# NASA DARES Focus Area 7

## Physical and Digital Architecture

### Focus Area 7 Team

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- Michael Tuite, Ph.D.
- Bruce Wilson, Ph.D.
- Tiffany Kataria, Ph.D.
- Robin Fergason, Ph.D. *(NASA Ex-Officio Member)*
- Jared Broddrick, Ph.D. *(Roving NASA Ex-Officio Member)*

# Sources Used

## Documents

- ~200 documents: Task Force 1 sources and output; subsequent NASEM and NASA reports; suggestions from TF2 and community
- All documents skimmed for relevance, human review of key documents
- Multiple AI summaries (Claude, ChatGPT, and Copilot); all human-validated

## Community webinars:

- 5 Community webinars: open science, data repositories & metadata, physical samples, AI/ML/Analytics, discussion with other FAs

## On-line environment:

- 50+ Astrobiology-relevant repositories and tools identified by TF2 members
- Surveyed repository and data discoverability, data and metadata standards, machine accessibility of data and metadata, and FAIR* data practices

* *FAIR: Findable, Accessible, Interoperable, Reusable (go-fair.org)*

# Overarching Finding #1

## Astrobiology spans many disciplines, each with distinct standards, vocabularies, and facilities requirements

### Causes and Impacts

- Disciplines use different and sometimes conflicting terminology and metadata
- Uncoordinated groups duplicate effort and leave gaps
- Astrobiology-relevant data often come from other fields
- ***No single standard, schema, or repository can serve all of astrobiology***

### Suggestions

- Adopt existing broad and extensible standards across the community
- Build on these standards with discipline-specific vocabularies
- Leverage and federate existing repositories rather than building from scratch
- Coordinate community working groups with programmatic support

# Overarching Finding #2

## Resource stewardship is systematically under-supported

### Causes and Impacts:

- Unique analog samples are at high risk of degradation and even loss
- Important data are often non-reusable, if not inaccessible
- Key facilities and capabilities are aging, uncoordinated, and lack capacity
- Work and effort at all scales are being duplicated or wasted

### Suggestions:

- **Provide visible long-term support for sample and data repositories**
- Explicitly provide for sample, data, and facility/capability stewardship roles
- Engage community in resource organization and prioritization
- Provide strong programmatic support for data, sample, and facility sharing
- Improve the discoverability of existing NASA facilities and capabilities

# People: Knowledge, Skills and Culture

## Lack of time, training, and appreciation for stewardship

**Causes and Impacts:** Research culture focuses on novel and high impact publications; haphazard training; lack of explicit support or incentive mechanisms; data and sample stewardship seen as only benefiting others.

**Suggestions:** Programmatically support stewardship roles; improve coordination and discoverability of key resources; assign and partner with repositories and shared facilities at project start.

## Data Science and AI/ML literacy gap

**Causes and Impacts:** High level of effort often needed to get data ready for analysis; AI and advanced analytics are less effectively used; senior expertise not fully utilized in data analysis (especially in AI model generation and use).

**Suggestions:** Build and encourage literacy programs across all career stages; integrate data science into astrobiology curricula; coordinate training for community-wide tools.

# Policies & Procedures

## Repositories face substantial sustainability challenges

**Causes and Impact:** Repositories fade or fold, leading to data and sample loss; dedicated repository funding looks expensive but can save money.

**Suggestions:** Evaluate actual costs and align support for overall efficiency and effectiveness; use longer-term support models for core infrastructure; consider CoreTrustSeal* criteria for repository sustainability best practices.

## Misaligned incentives block open science adoption

**Causes and Impacts:** Easier to fund *new* than *sustain,* leading to reinvention and fragmentation; funding for coordination groups often only supports travel.

**Suggestions:** Acknowledge the value of data & methods publications (e.g., in hiring, recognition, and proposal selection); establish an "Astrobiology Data Council" to develop and support standards; support community working groups without requiring volunteer labor.

* *CoreTrustSeal – Core Trustworthy Data Repositories*

# Digital World: Data, Tools & Computing

## Astrobiology data ecosystem is not FAIR* or AI-ready

**Causes and Impacts:** Hard to discover and access data; lack of APIs and consistent standards greatly limits usability, especially by AI and ML; legacy, offline, and sole-PI data at high risk of loss.

**Suggestions:** Prioritize machine accessibility and interoperability of data and metadata; promote use of existing standards for general metadata (schema.org); consider interdisciplinary repository registration (re3data.org).

## A strategy spanning digital and physical infrastructure needed

**Causes and Impacts:** Mission data volumes exceed high-end computing (HEC) capacity; redundant data repositories and AI/ML tools developed independently across centers; lack of plan for integrating AI/ML skills into workforce; missions limited by DSN capacity.

**Suggestions:** Co-locate computation with data; support community data science training and validation standards; ensure HEC and foundation model strategy is coordinated across centers and programs.

* *FAIR: Findable, Accessible, Interoperable, Reusable (go-fair.org)*

# Physical World: Samples & Facilities

## Gaps abound in sample repositories

**Causes and Impacts:** No integrated approach to terrestrial analog curation; flight instruments are not cross-comparable due to a lack of common reference suites.

**Suggestions:** Develop and implement a federated sample repository strategy; partner with existing repositories to expand coverage of terrestrial analog samples, support for non-rock samples, and lessons learned; establish accessible abiotic standard samples.

## Field and lab infrastructure are under-supported

**Causes and Impacts:** Inadequate capacity for mid-range Technology Readiness Level (TRL) testing; sample return containment unresolved.

**Suggestions:** Consider establishing standing planetary analog field stations; co-locate instrument facilities with sample access; improve access to flight-like instruments; assess cross-disciplinary needs and opportunities for mutual support (particularly Earth science).

# NASA DARES Focus Area 8

## Early Career and Workforce Development

### Focus Area 8 Team

- Christina Richey, Ph.D. *(Lead)*
- Catherine Fontana *(Executive Secretary)*
- Billy Brazelton, Ph.D.
- Julie Castillo-Rogez, Ph.D.
- James Roberts, Ph.D.
- Nicolle Zellner, Ph.D.
- Melissa Kirven-Brooks, Ph.D. *(NASA Ex-Officio Member)*

# FA8: From TF1 to efforts in TF2

We need supportive work environments and career development resources to achieve our astrobiology goals.

### Early Career Researchers

- Careers in astrobiology have unique challenges that require support
- How do we support ECRs distributed among disciplines and institutions?

### Sources of Funding

- ROSES programs alone are not sufficient to support a robust astrobiology workforce
- How do we develop other funding streams that can include workforce support?

### Science Networks

- Scientific societies and other peer groups should be further developed and supported
- How can NASA Research Coordination Networks (RCNs) provide more enduring workforce support?

### Broaden the Community

- Subject matter experts (SMEs) from beyond the astrobiology community should be recruited
- How can we firmly establish astrobiology in more institutions?

### Collaborations

- Astrobiology can be better integrated into intra- and inter-agency partnerships
- How can we improve our international partnerships in astrobiology?

## Astrobiology has matured as a research field since 2015

- Astrobiology research topics are now well-established within NASA and beyond
- However, institutional support for training and career development is still lacking
- Graduate programs dedicated to astrobiology have not grown since 2015
- Very few jobs are advertised as astrobiology-specific
- Early career researchers are often isolated and struggle to stay in the field

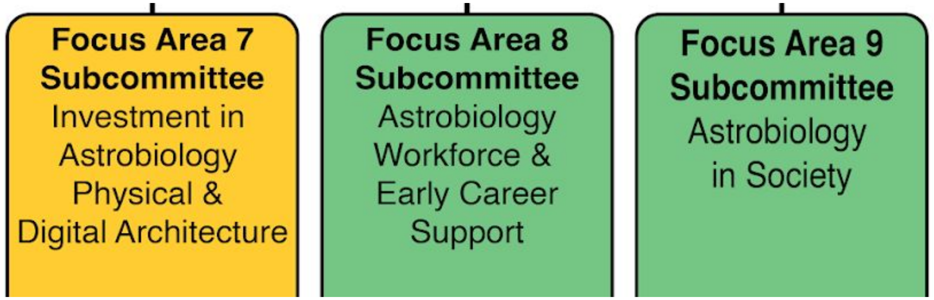
## Motivation for FA8: Understanding the state of the workforce is critical for maintaining research excellence and mission success

- Early career researchers (ECRs) are often very passionate and dedicated, but they lack institutional support mechanisms available to ECRs in many other fields
- Many astrobiologists have faced unprecedented challenges in recent years that need to be better understood and addressed
- **Our goal is to highlight examples of success as well as specific areas that require attention in the future**

## The state of the workforce is a critical component of a national strategy document

- Astrobiology 2015 strategy did not mention the workforce
- Recent NASEM strategy documents have included workforce issues
- We have mapped FA8 themes to >10 decadal reviews and other strategy documents

| Short / Colloquial Name | Year/Org | Connection to FA8 |
|---|---|---|
| Astrobio 2015 Strategy | 2015/NASA | Weak |
| Astrobio 2019 Strategy | 2019/NASEM | Weak |
| Astro2020 | 2020/NASEM | Strong |
| SSERVI | 2021/SSRP | Some |
| NASA at a Crossroads | 2022/NASEM | Some |
| Healthy and Vital Community | 2022/NASEM | Strong |
| Leadership of Competed Space Missions | 2022/NASEM | Strong |
| Thriving in Space | 2023/NASEM | Some |
| OWL | 2023/NASEM | Strong |
| Human Expo of Mars | 2025/NASEM | Weak |
| Solar and Space Physics | 2025/NASEM | Strong |




FA8 has heavy cross over with FA7 & FA9, but also implications across all FAs.

# Recap of Webinars/Discussions by FA8

- Review of TF1 FA8 Findings and Scope of Work for FA8
- Early Career Researcher Panel
- Using Demographic Information to Understand the Workforce
- Astrobiology Centers Q&A
- Created feedback form for preliminary understanding of community needs

# Themes and Findings

## 1. Challenges faced by the current astrobiology workforce

- **The astrobiology community is losing talented people due to inconsistent workforce support and challenging working conditions.**
  - **Next steps:** Study retention as a major challenge for the astrobiology community; explore causes and potential solutions.
- **The transition from NAI to RCNs has introduced both challenges and opportunities.**
  - **Next steps:** Investigate gaps in workforce support and career development; continued focus on community building to complement research teams.
- **Astrobiology ECRs are passionate, dedicated, and require more structure for career development.**
  - **Next steps:** Build institutional and programmatic structures for career development; train students for flexible employment options; enact policies regarding compensation for service work by ECRs.

# Themes and Findings

## 2. A better understanding of the astrobiology workforce is necessary

- **A systematic approach for gathering information and studying our workforce is required.**
  - **Next steps:** Gather demographic data; fund an effort to study the astrobiology workforce; make the data and analyses open and transparent.
- **Tools and resources for career development are unevenly distributed within the astrobiology community.**
  - **Next steps:** Promote training opportunities for ECRs who are not already connected to funded research teams; centralize resources for training, funding, research, and social opportunities.
- **Professional societies can provide workforce support independent of funding agencies.**
  - **Next steps:** Support efforts to develop professional societies; explore paths to increasing cohesion and integration within an interdisciplinary community.

# Themes and Findings

## 3. Recruitment, retention, and professional development

- **Education (K-12 to undergraduate/graduate and beyond) is a critical component of the astrobiology workforce.**
  - **Next steps:** Investigate institutional support for astrobiology education; support curricula development; promote national and international coordination.
- **Astrobiology centers play a central role in training and career development.**
  - **Next steps:** Study the successes and failures of research centers, support research centers in providing career development resources, including workshops, summer schools, and conferences.
- **There are very few astrobiology-specific jobs compared to the number of students interested in / studying astrobiology.**
  - **Next steps:** Study employment outcomes and the causes and consequences of retention failures; improve institutional support for career transitions to avoid unnecessary losses of talent; train students to navigate multifaceted career paths including academica, government, industry, non-profit opportunities.

# NASA DARES Focus Area 9

## Astrobiology in Society

### Focus Area 9 Team

- Sara K. Yeo, Ph.D. *(Lead)*
- Dani Buchheister *(Executive Secretary)*
- Danilo Albergaria, Ph.D.
- Sheri Wells-Jensen, Ph.D.
- Andreas Schwarz, Ph.D.
- Becky McCauley Rench, Ph.D. *(NASA Ex-Officio Member)*
- Daniella Scalice *(Ex-Officio Support)*

# Focus Area 9 slides are forthcoming.

# Summary

- The cross-disciplinary reach of astrobiology is expanding as the field grows: this presents major opportunities but increases the need for clear definitions & shared frameworks
- **Expanding frontiers:** Astronomy, human exploration program, new life detection technologies, AI/ML, technosignatures, society and humanities
- Origin-of-life research needs deeper integration with missions and stronger ECR support
- Integrated, interdisciplinary study of the planetary context is critical to understanding pathways to biogenesis, habitability and life
- Robust life detection requires shared standards of evidence and characterization of the abiotic background
- **Major challenges include:**
    - Technology and mission architecture gaps
    - Data standardization & metadata infrastructure
    - Workforce stability, basic research funding and morale issues

# Public Comment Period & Steps to Publication

- An extended slide deck describing the DARES draft strategy will be uploaded to the DARES website on **June 2nd**.
- This will commence a **1-month public comment period**; comments should be sent to HQ-RFIAstrobio@mail.nasa.gov. A **formal announcement** will be made via the **Astrobiology Mailing List** and **NASA-DARES website**.
- DARES Task Force 2 will incorporate public comments and write the final strategy document through summer 2026.
- DARES Task Force 2 will host a final **virtual community round table** in **early fall 2026** to present the final strategy before internal agency review.
- The **final strategy** will be released at **AGU Fall Meeting in December 2026**.

NASA-DARES website

Astrobiology Mailing List